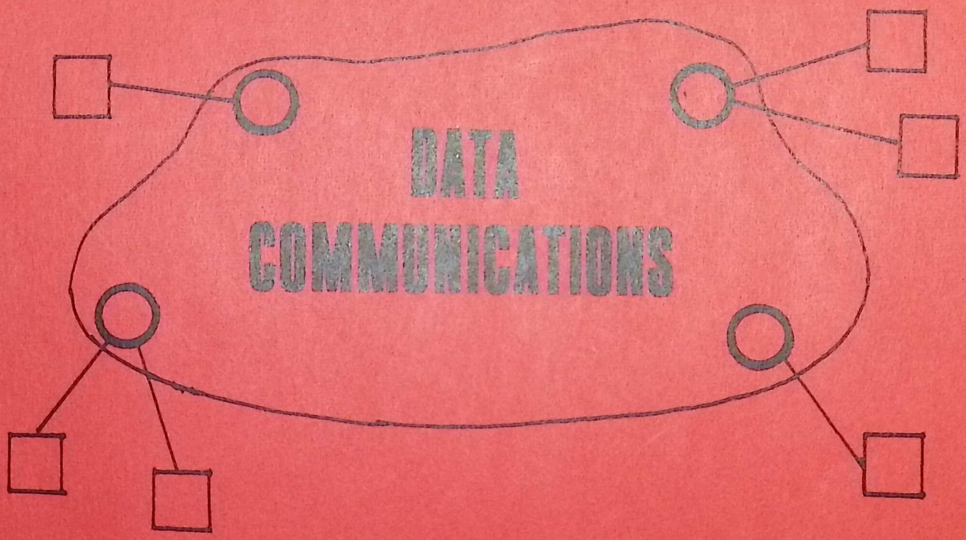
Ford

UNITED STATES AIR FORCE ACADEMY

Department of Electrical Engineering



Version 1.2

384

COURSE OBJECTIVES AND DESCRIPTION

THE COURSE IS DESIGNED TO INTRODUCE DATA COMMUNICATION TERMINOLOGY, CONCEPTS, AND SYSTEM DESIGN TO GOVERNMENT COMMUNICATION ENGINEERS, MANAGERS, AND ANALYSTS.

THE COURSE PROVIDES PARTICIPANTS HAVING EXPERIENCE IN BASIC COMMUNICATIONS WITH AN INTRODUCTION TO HARDWARE AND SOFTWARE APPLICATIONS IN DIFFERENT NETWORK TYPES. CONCEPTS ARE ILLUSTRATED BY EXAMPLES AND SOME IN-CLASS EXERCISES.

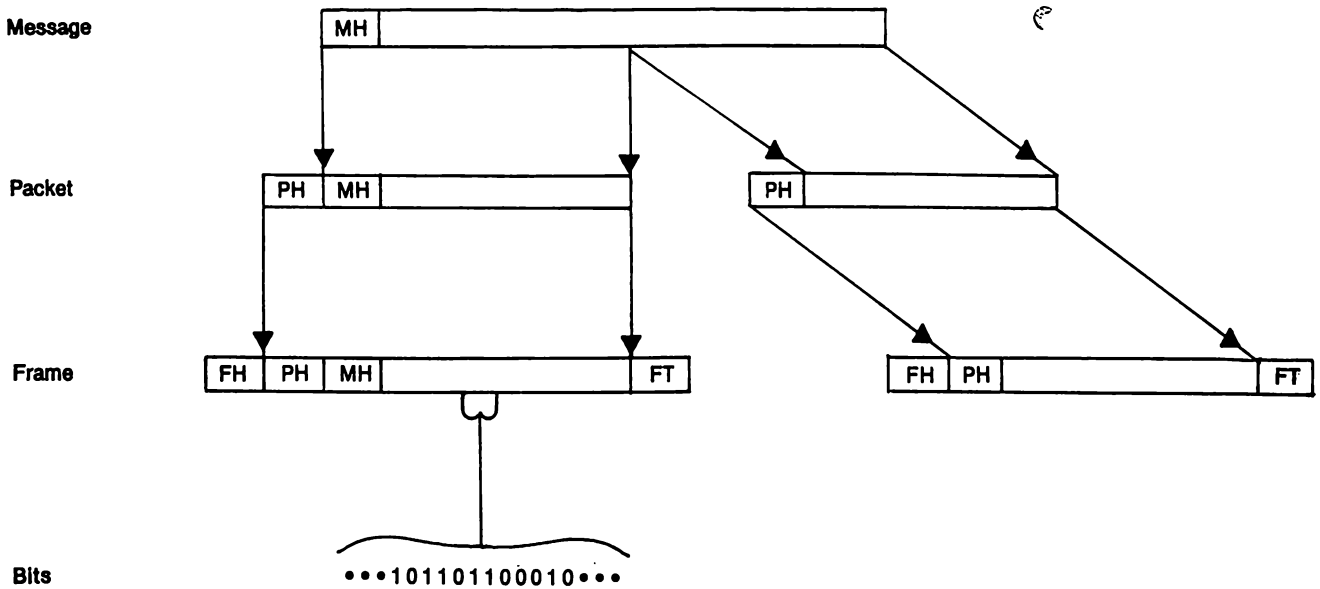
DATA

COMMUNICATIONS

SCHEDULE

DAY 1			DAY 2			DAY 3		
0800		Course Admin.	0800	3.1	Common Carriers	0800	5.1	Multiplexing/Concentration
0830	1.1	Introduction	0900	3.2	Data Link Protocols	0900	5.2	Transport Protocols
0915	1.2	Transmission Media	1000		Break	1000		Break
0945		Break	1015	3.2	Data Link Protocols	1015	5.3	Digital Voice Comm
1000	1.3	Bit Transmission	1030	3.3	Broadcast Network Protocols	1130		Lunch
1130		Lunch	1130		Lunch	1300	6.1	Topology Design
1300	2.1	Modems/Interfaces	1300	4.1	Pt - to - Pt Network Protocols	1315	6.2	The M/M/1 Network
1430		Break	1430		Break	1345	6.3	Delay Analysis
1445	2.2	Codes/Coding	1445	4.2	Local Network Protocols	1430		Break
1630		End Day 1	1630		End Day 2	1445	6.4	Capacity Assignment
						1540	6.5	Protocol Analysis
						1630		End Day 3

DATA UNIT RELATIONSHIPS



(T: p. 13)

1.1 INTRODUCTION / MODEL (STANDARDS)

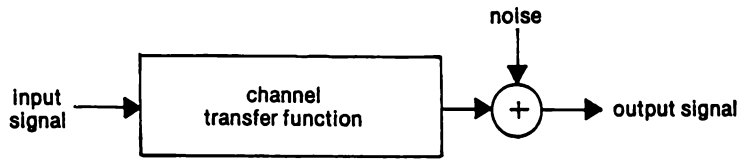
- Standards Organizations
  - International Telephone and Telegraph Consultative Committee (CCITT)
    - Committee of International Telecommunications Union, a UN organization
    - US members: Department of State, A.T. & T
  - International Standards Organization (ISO)
    - Voluntary organization of national standards organizations
    - US member: ANSI
  - American National Standards Institute
    - Open membership
  - Electronic Industries Association (EIA)
    - Membership includes most US manufacturers of electronic equipment

(M: pp. 39-40)

(T: pp. 97-98)

1.2 TRANSMISSION MEDIA CHARACTERISTICS

MODEL/PARAMETERS



- Linear, nonlinear and real channels
- Channel transfer function parameters
  - Frequency response
  - Phase response
  - Delay
- Noise
  - Thermal
  - Impulse / Shot
  - Intermodulation
  - Crosstalk

(ZT: pp. 3-8)

LINEARITY

- Linear vs. non-linear vs. real channels

- Linear channels

  Input : $A_1 \cos(2\pi f_1 t + \theta_1) + A_2 \cos(2\pi f_2 t + \theta_2)$

  Output: $B_1 \cos(2\pi f_1 t + \phi_1) + B_2 \cos(2\pi f_2 t + \phi_2)$

- Non-linear channels

  Input : $A_1 \cos(2\pi f_1 t + \theta_1) + A_2 \cos(2\pi f_2 t + \theta_2)$

  Output: $B_1 \cos(2\pi f_1 t + \phi_1) + B_2 \cos(2\pi f_2 t + \phi_2)$

  $+ B_3 \cos(2\pi (f_1 + f_2) t + \phi_3)$

  $+ B_4 \cos(2\pi (f_1 - f_2) t + \phi_4)$

  $+ \cdots$

- Real channels are, in general, non-linear; but are usually close enough to linear so that intermodulation products are small.

(M: pp. 512-513)

1.2 TRANSMISSION MEDIA CHARACTERISTICS

- Frequency response
  - Measured by placing a constant amplitude sinusoidal signal on input and observing the amplitude of the output
  - Real channels
    - Lowpass
    - Bandpass
  - Bandwidth
  - Frequency distortion

1.2 TRANSMISSION MEDIA CHARACTERISTICS

PARAMETERS

- Phase Response
  - Relative measurement using a constant amplitude sinusoidal signal on input and comparing phase of output with input
  - Phase distortion, phase delay or envelope distortion
- Delay
  - The amount of time for a signal to go through the channel

NOISE

- Thermal Noise
  - Due to random motion of electrons
  - Noise power, $N = kTB$

    $k = 1.38 \times 10^{-23}$ (Joule/°k)

    T = effective circuit temp (°k)

    B = bandwidth (Hz)
  - Noise power per Hertz is constant, "white" noise
- Impulse Noise
  - Due to rapid perturbations of channel or external interference
- Intermodulation
  - Due to channel not being perfectly linear
- Cross talk
  - Due to signals other than the desired one electromagnetically coupling into channel

(ZT: pp. 469-476)

(M: pp. 507-513)

1.2 TRANSMISSION MEDIA CHARACTERISTICS

EXAMPLES

Media	Bandwidth	Delay	Noise
Telephone	3KHz	6μs/Km	Thermal, Impulse
H F Radio	5KHz	6μs/Km	Impulse
Terrestrial Microwave	100MHz	6μs/Km	Thermal
Satellite Transponder	> 100MHz	> 540mS	Thermal
Fiber Optics	1GHz	> 6μs/Km	Thermal, Impulse

(M: pp. 156-186)

1.3 BIT TRANSMISSION (OVERVIEW)

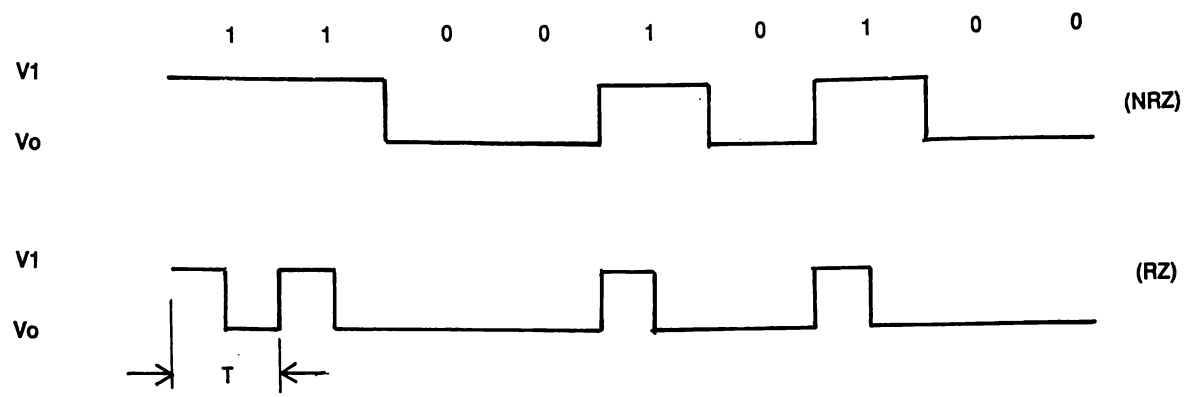
- Types
  - Baseband
  - Modulation
- Main concern is to match spectral density of bit stream to channel bandwidth
- Fundamental Limits
  - Shannon
  - Nyquist

1.3 BIT TRANSMISSION (BASEBAND)

Baseband

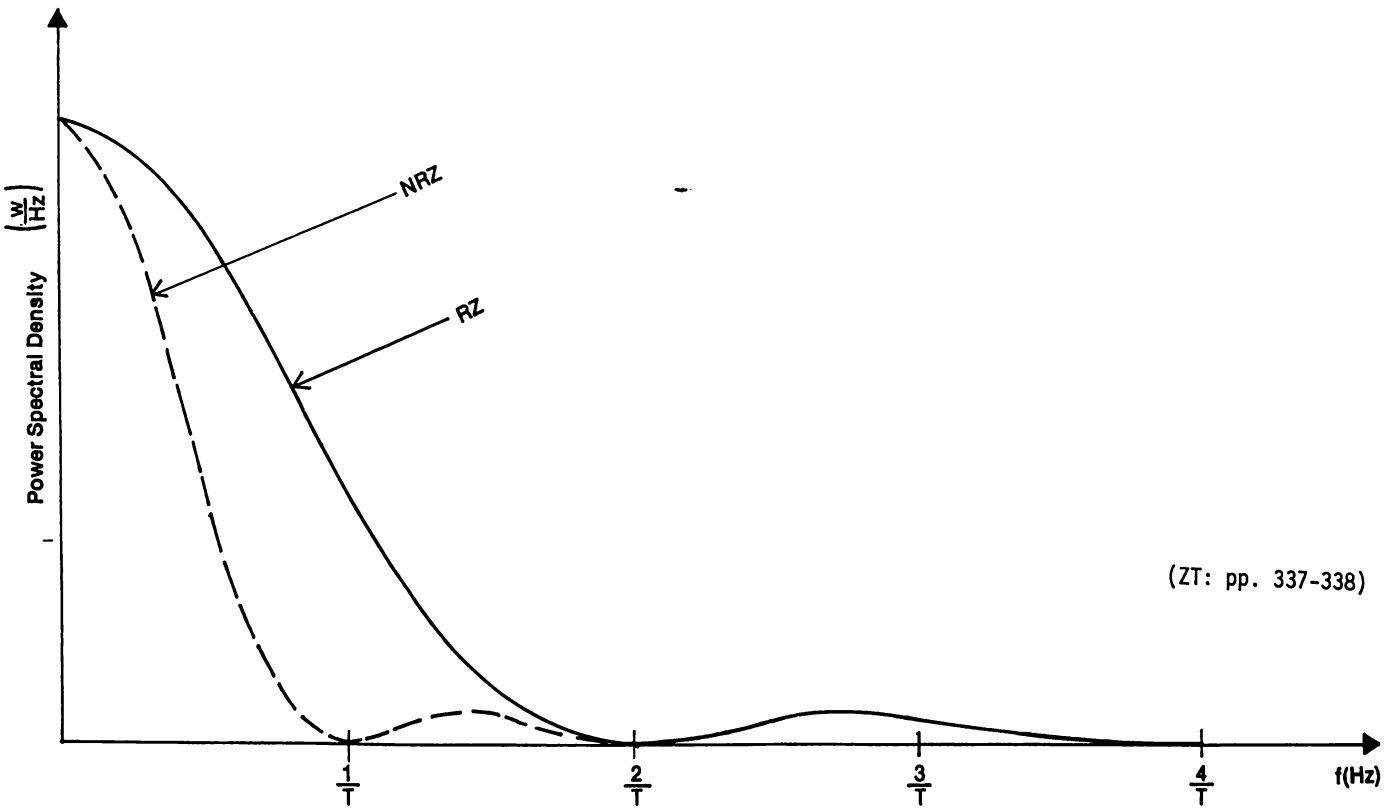
- Bit stream without modulation
- Bit synchronization
- Want no low frequency energy
- Want compact spectral distribution
- Simple implementation

- Non Return to Zero (NRZ) and Return to Zero (RZ) signals



(ZT: pp. 337-338)

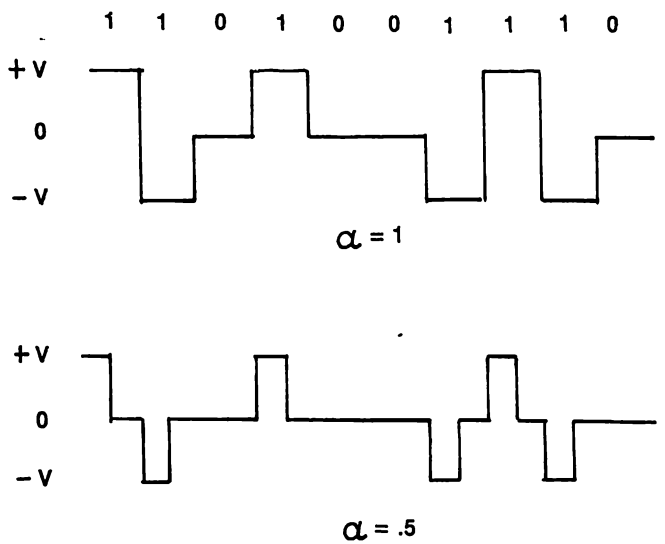
1.3 BIT TRANSMISSION (BASEBAND)

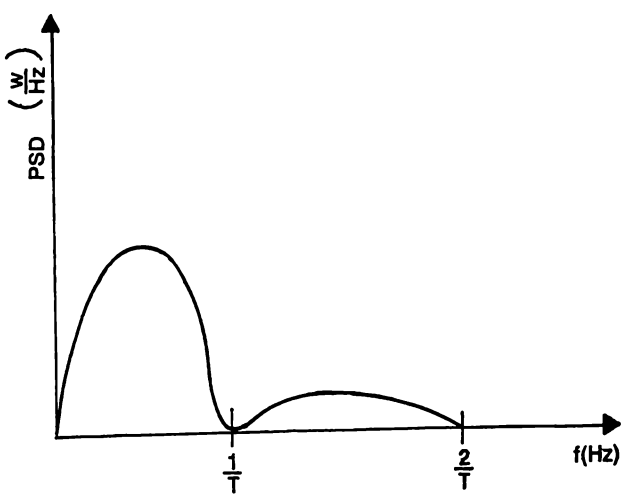


(ZT: pp. 337-338)

1.3 BIT TRANSMISSION (BASEBAND)

- Bipolar Baseband Signals
  - Also called pseudoternary or alternate mark invert
  - Zero represented by 0 voltage, one by $\pm$V pulse, where polarity of V alternates with successive ones.
  - Pulse Duration $= \alpha T$, where T is the bit duration and $0 < \alpha \leq 1$
  - Pulses are statistically dependent with error detection capability
  - No DC component





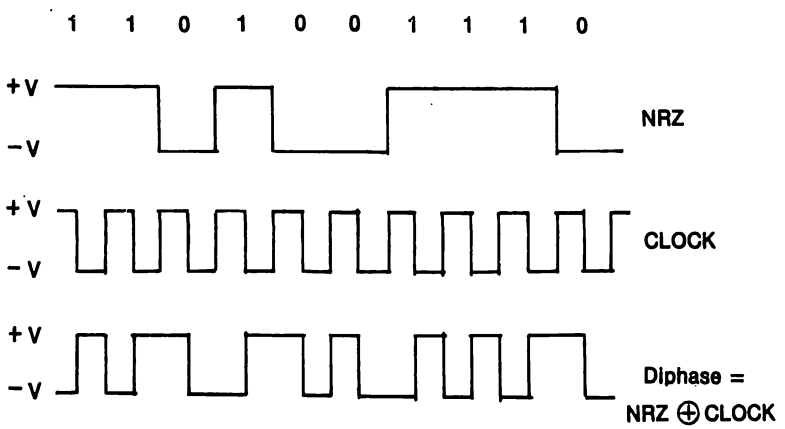
(ZT: pp. 337-338)

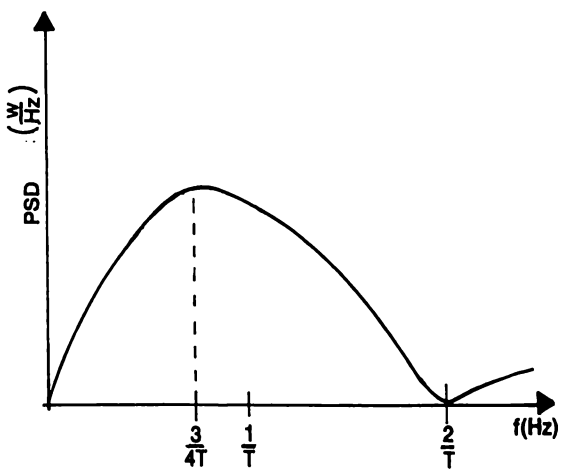
1.3 TRANSMISSION (BASEBAND)

- Diphase Baseband Signal
  - Also called split phase or Manchester code
  - Bit internal consists of two equal length pulses

    Zero : +V, −V

    One : −V, +V
  - Increased Number of Transitions
  - Very little low frequency power



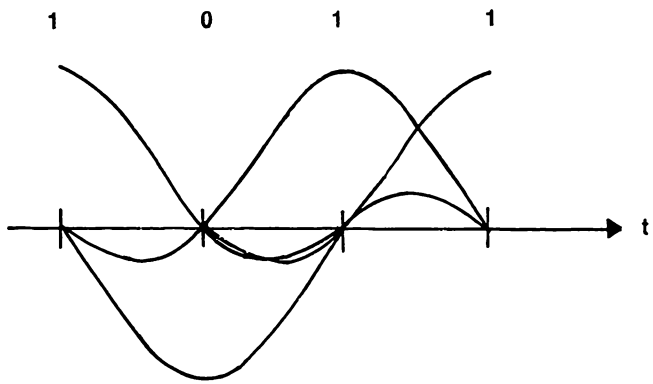


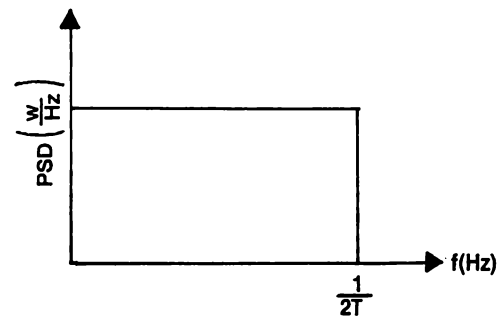
(ZT: pp. 337-338)

1.3 BIT TRANSMISSION (BASEBAND)

- Sinc baseband signal
  - Maximum data rate for band limited channel
  - Difficult to maintain synchronization
  - No intersymbol interference due to zero crossings

$$\text{sinc}(x) = \frac{\sin \pi x}{\pi x}$$





1.3 BIT TRANSMISSION (MODULATION)

- Modulation
  - Varying parameter(s) of a sinusoidal carrier in accordance with binary information
  - May be single or double step operation
  - Types

    Amplitude Modulation/Amplitude Shift Keying (AM/ASK)

    Frequency Modulation/Frequency Shift Keying (FM/FSK)

    Phase Modulation/Phase Shift Keying (PM/PSK)

    Combinations of the above

  - Bit Rate versus Baud Rate

    Bit rate ≡ Rate of transmitted binary digits in bits/sec

    Baud rate ≡ Rate of transmitted channel signals is symbols/sec or baud

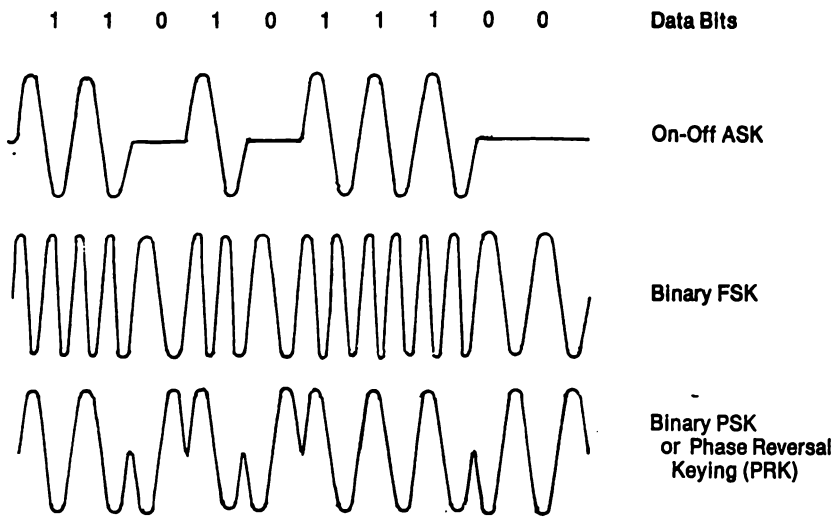
(T: p. 100)

(M: pp. 203-228)

(D: p. 160)

1.3 TRANSMISSION (MODULATION)

- Waveform examples



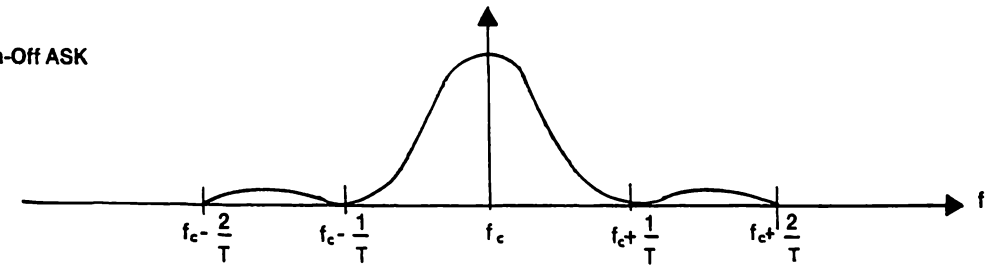
Duration of each bit = T seconds

1.3 BIT TRANSMISSION (MODULATION)

- Resulting Spectra and Bandwidth

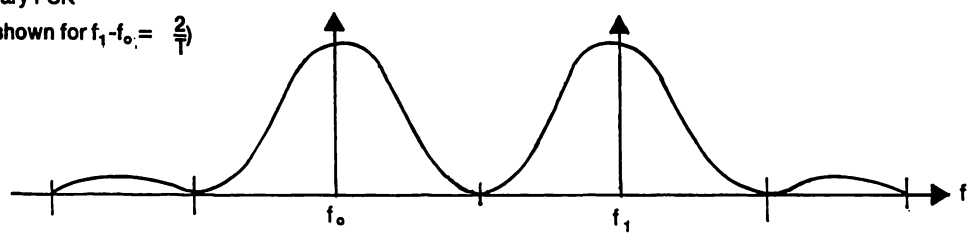
On-Off ASK

$BW \approx \frac{2}{T}$



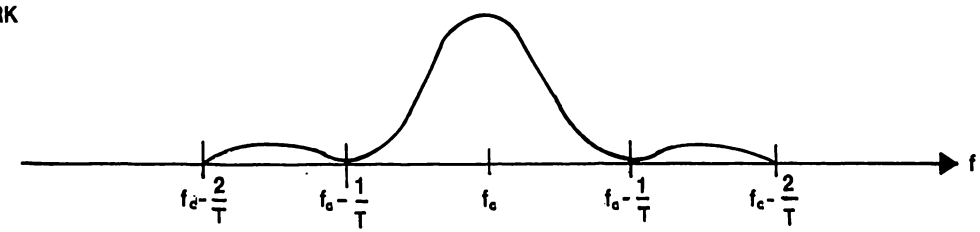
Binary FSK
(shown for $f_1 - f_o = \frac{2}{T}$)

$BW \approx \frac{2}{T} + (f_1 - f_o)$



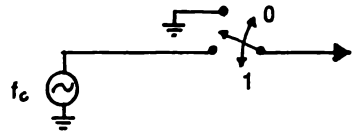
PRK

$BW \approx \frac{2}{T}$

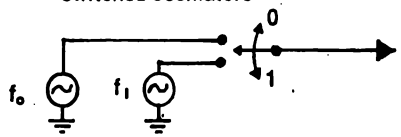


1.3 BIT TRANSMISSION (MODULATION)

- Modulator
  - On-Off ASK

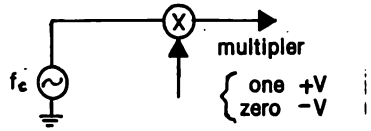


  - Binary FSK
    - switched oscillators



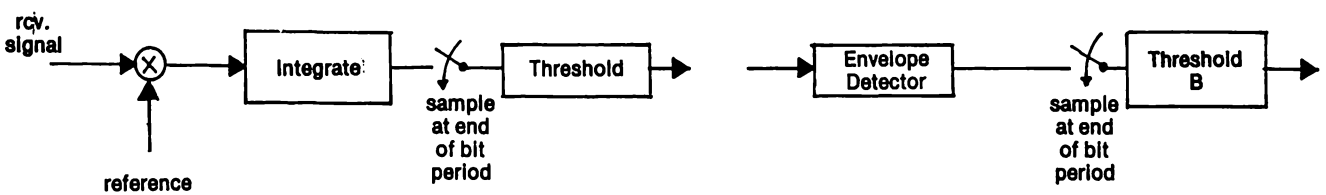
    - voltage controlled oscillator (VCO)
    - switched oscillators easier to implement but has but has phase discontinuities

  - PRK



1.3 BIT TRANSMISSION (DEMODULATION)

- Demodulation
  - Coherent - requires in-phase carrier reference at demodulator
  - Non coherent - does not require carrier reference
- On - Off ASK



Coherent

$$P_E = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E_b}{2N_0}}$$

$$E_b = \frac{A^2 T}{4}$$

Non-Coherent

$$P_{E,0} = \frac{1}{2} e^{-B^2/N_0}$$

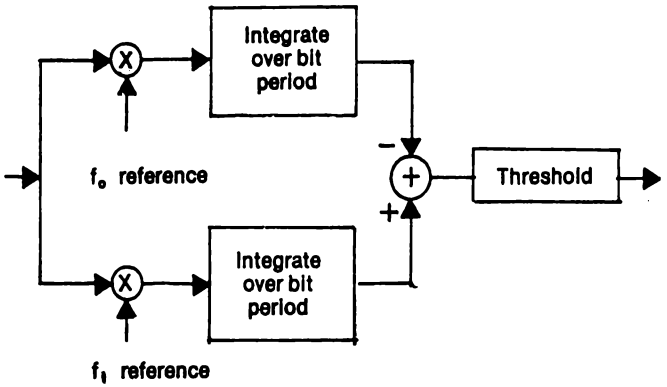
$$P_{E,1} = \frac{1}{2}\left(1 - Q_m\left(\frac{A\sqrt{2}}{\sqrt{N_0}}, \frac{B\sqrt{2}}{\sqrt{N_0}}\right)\right)$$

$$E_b = \frac{A^2 T}{4}$$

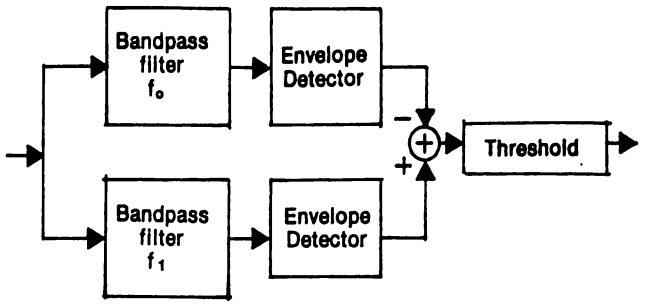
(ZT: pp. 319, 326-330)

1.3 BIT TRANSMISSION (DEMODULATION)

- Binary FSK



Coherent



Non-Coherent

$$P_E = \frac{1}{2}\,\mathrm{erfc}\sqrt{\frac{E_b}{2N_o}}$$

$$P_E = \frac{1}{2}e^{-E_b/2N_o}$$

$$E_b = \frac{A^2T}{2}$$

$$E_b = \frac{A^2T}{2}$$

(ZT: pp. 323, 330-331)

1.3 BIT TRANSMISSION (DEMODULATION)

- PRK
  - Coherent Demodulator is same as On - Off ASK

$$P_E = \frac{1}{2} \operatorname{erfc} \sqrt{\frac{E_b}{2N_0}} \qquad E_b = \frac{A^2 \cdot T}{2}$$

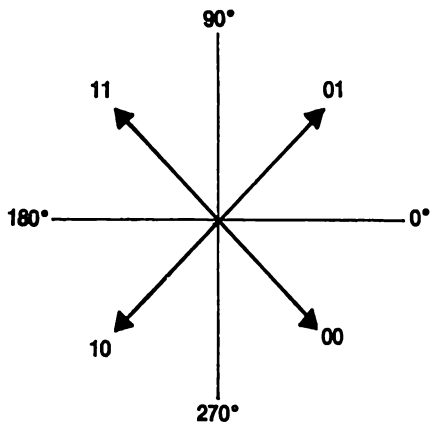
  - Differentially Coherent Demodulation - compare phases of successive samples

$$P_E = \frac{1}{2} e^{-\left(E_b/N_0\right)} \qquad E_b = \frac{A^2 T}{2}$$

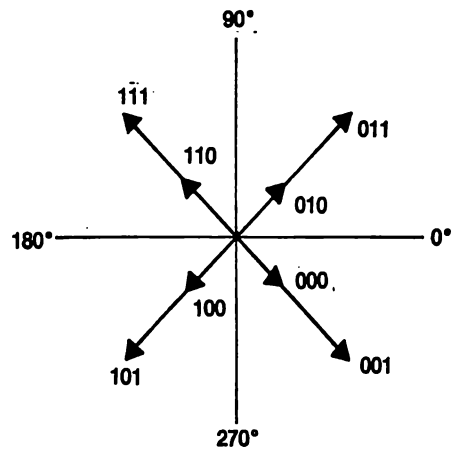
(ZT: pp. 320-326)

1.3 BIT TRANSMISSION (MODULATION)

- Combinations and other modulation schemes
  - Quadrature amplitude modulation (QAM)
  - Multitone Frequency Shift Keying
  - Multiple Phase Shift Keying (MSK)
  - Differential Encoding



MSK
(Quadrature PSK)



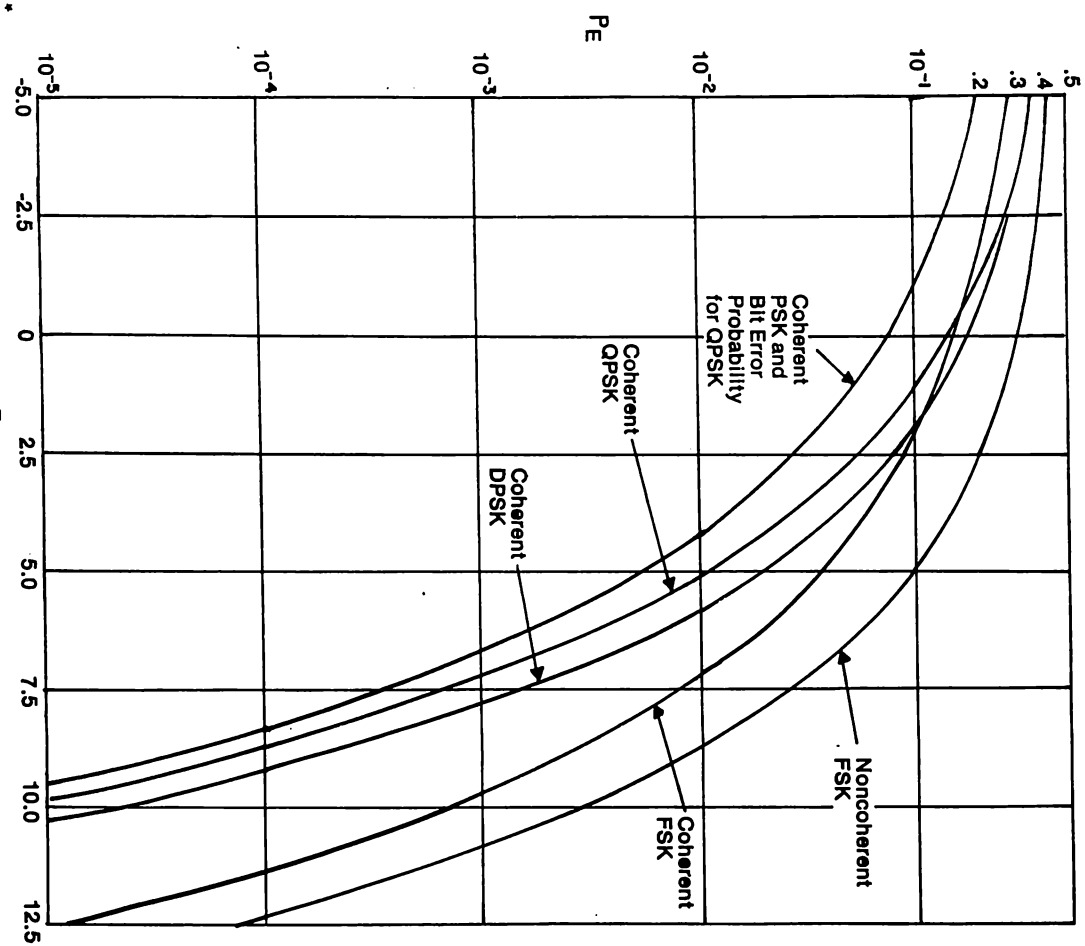
QAM

(M: pp. 226-228)

(D: pp. 197-201)

(ZT: pp. 324, 332-336)

1.3 BIT TRANSMISSION (ERROR PROBABILITIES)



(ZT: pp. 331, 337)

1.3 BIT TRANSMISSION (FUNDAMENTAL LIMITS)

- Nyquist (Assumes noiseless channels)

  $C = 2B \log_2 V$

  C channel capacity (bits per second)

  B channel bandwidth (Hertz)

  V Number of symbols

- Shannon

  $C = B \log_2 (1+\frac{S}{N})$

  C channel capacity (bits per second)

  B channel bandwidth (Hertz)

  S signal power (Watts)

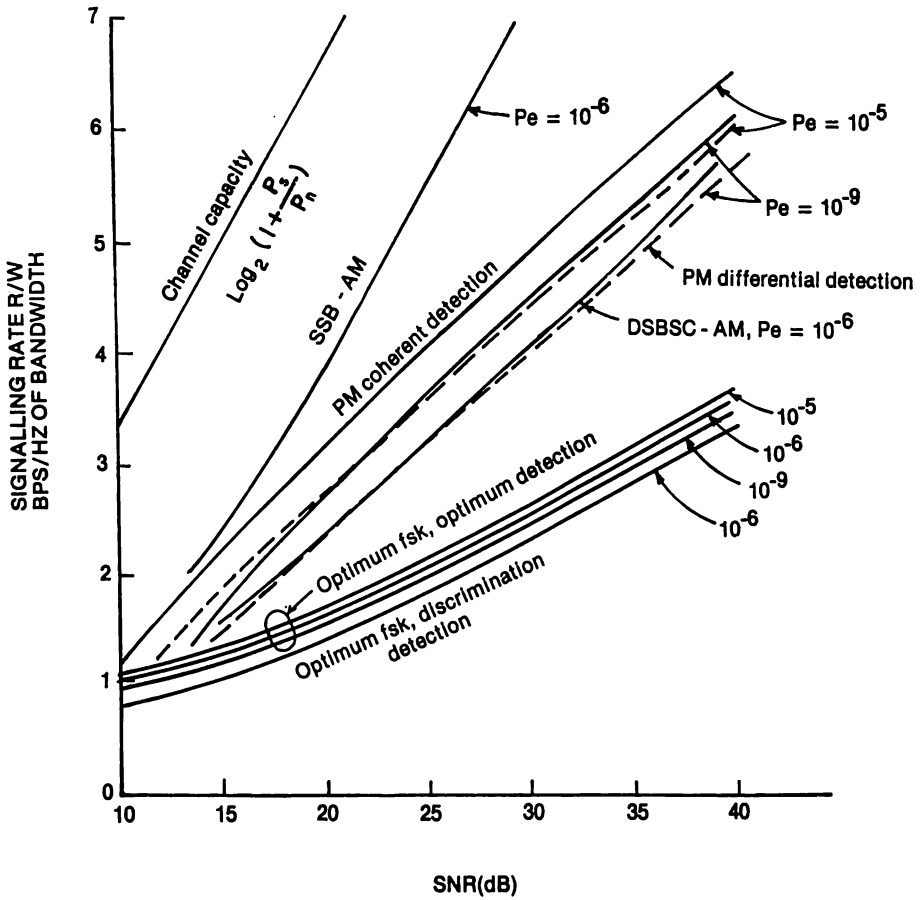
  N noise power (Watts)

(D: pp. 157-162)

(M: pp. 302-314)

(T: pp. 95-96)

1.3 BIT TRANSMISSION (BANDWIDTH EFFICIENCY)



(M: p. 309)

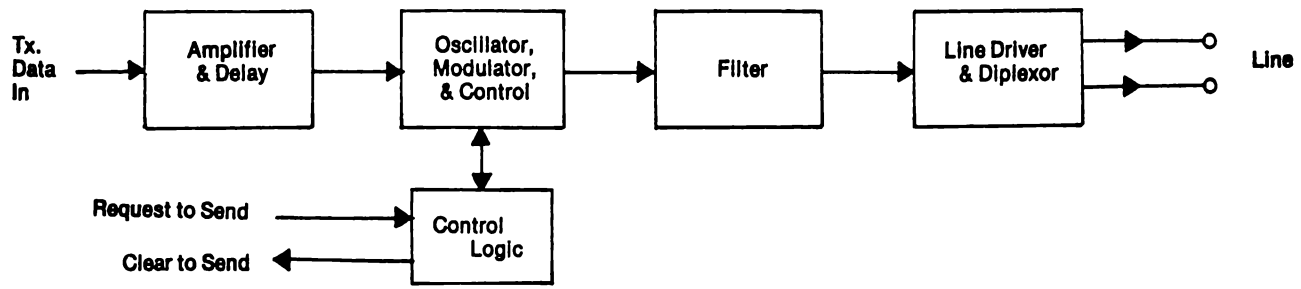
(ZT: pp. 459-462)

2.1 MODEMS/INTERFACES (OVERVIEW)

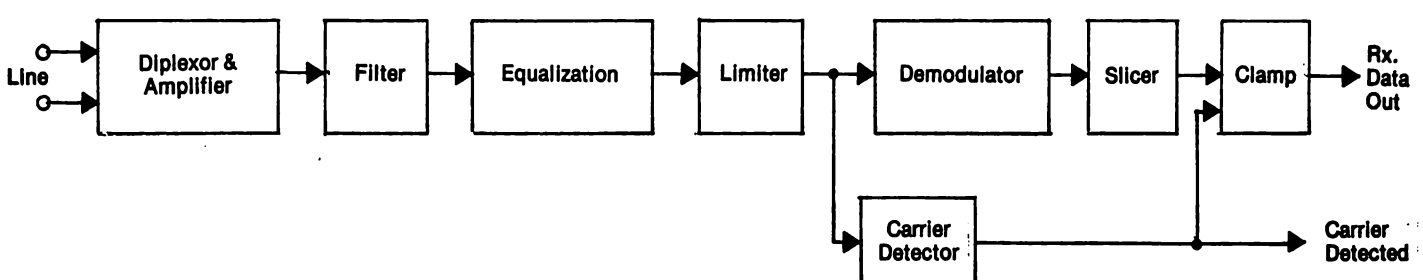
- Modems
  - Basic Function
  - Special Features
  - Bell Modems
  - Limited Distance Modems
  - Connection to telephone lines
- Interfaces
  - RS - 232C
  - RS - 422
  - RS - 423
  - RS - 449

2.1 MODEMS/INTERFACES (BASIC FUNCTION)

Modem Transmitter



Modem Receiver



(M: pp. 222-223)

2.1 MODEMS/INTERFACES (MODES)

- Simplex
- Half Duplex
  - Control signals for carrier switching
  - Turnaround times
- Full Duplex
  - Control signals
  - Channel division (originate/answer)
- Synchronous
- Asynchronous
- 2 wire / 4 wire

(D: pp. 65-71, pp. 191-197)

2.1 MODEMS/INTERFACES (SPECIAL FEATURES)

- Automatic calling/answering
- Reverse control channel
- Circuit quality monitor
- Local and remote loopback
- Built-in data access arrangements
- Automatic adaptive equalization
- Split streaming

(D: pp. 202-204)

2.1 MODEMS/INTERFACES (BELL MODEMS)

Model	Speed (bps/baud)	Modulation	Modes		
103A	300/300	FSK	asynch	H/FDX	2w
113A	300/300	FSK	asynch	H/FDX	2w
113B	300/300	FSK	asynch	H/FDX	2w
201A	2000/1000	PSK (4~)	synch	H/FDX	2/4w
201B	2400/1200	PSK (4~)	synch	H/FDX	2/4w
201C	2400/1200	PSK (4~)	synch	H/FDX	2/4w
202C	(1200/1200 1800/1800)	FSK	asynch	H/FDX	2/4w
202D	(1200/1200 1800/1800)	FSK	asynch	H/FDX	2/4w
202R	(1200/1200 1800/1800)	FSK	asynch	H/FDX	2/4w
202S	1200/1200	FSK	asynch	HDX/SMPX	2w/4w
202T	(1200/1200 1800/1800)	FSK	asynch	H/FDX	2/4w
208A	4800/1600	PSK (8~)	synch	H/FDX	2/4w
208B	4800/1600	PSK (8~)	synch	HDX	2/4w
209A	9600/1600	QAM	synch	H/FDX	2/4w
212A	(300/ 300 1200/1200)	(FSK PSK)	(asynch synch)	H/FDX	2/4w

LIMITED DISTANCE MODEMS/CONNECTIONS

- Limited distance modems
  - Also known as short haul or baseband modems or line drivers
  - Used for short distances over dedicated channels
  - Analog modems - PRK or BFSK
  - Digital modems - baseband signals
- Connection to telephone lines
  - Acoustic coupler
  - Data access arrangement
  - Direct connection

(D: p. 209)

(M: p. 322, 335)

2.1 MODEMS/INTERFACES

- Interface
  - The physical, electrical, and logical rules for exchanging data between the DTE and DCE
  - Typically specifies
    - number of wires
    - maximum cable length
    - connectors
    - voltage levels
    - impedances
    - rise/fall times
    - logic signal functions

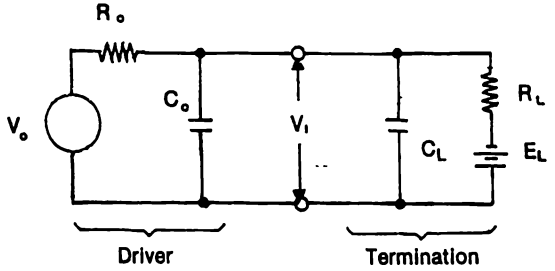
2.1 MODEMS/INTERFACES (EIA RS232C)

- Serial binary data transfer
- 20 K bps maximum data rate
- 50 foot maximum cable length
- Synchronous or asynchronous transmission
- Half duplex or full duplex transmission
- DB-25, 25 pin connector
- Roughly equivalent to CCITT V.24

(M: pp. 325-328)

(D: pp. 244-242)

2.1 MODEMS/INTERFACES (EIA RS 232C)



V_o	open circuit driver voltage	$3\,V \leq \lvert V_o \rvert \leq 25V$
R_o	driver internal resistance	$> 300\ \Omega$
C_o	total effective capacitance of driver	not specified
V_i	interface point voltage	≤ -3 V (mark/off)
		$\geq +3$ V (space/on)
C_L	total effective capacitance of termination	< 2500 pF
R_L	terminator load resistance	$3K\,\Omega < R_L < 7K\,\Omega$
E_L	open circuit terminator voltage (bias)	< 2 V
	slew rate through transition region	lesser of 1ms or 4% of bit duration

(D: p. 246)

(M: pp. 122-131)

2.1 MODEMS/INTERFACES (EIA RS 232C)

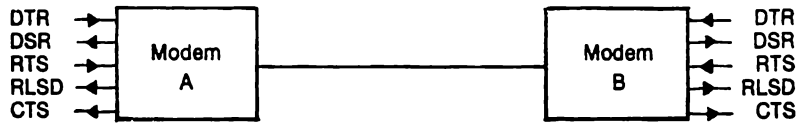
Pin Number	Interchange Circuit	C.C.I.T.T. Equivalent	Description	Gnd	Data		Control		Timing	
					From DCE	To DCE	From DCE	To DCE	From DCE	To DCE
1	AA	101	Protective Ground	X						
7	AB	102	Signal Ground/Common Return	X						
2	BA	103	Transmitted Data			X				
3	BB	104	Received Data		X					
4	CA	105	Request to Send					X		
5	CB	106	Clear to Send				X			
6	CC	107	Data Set Ready				X			
20	CD	108.2	Data Terminal Ready					X		
22	CE	125	Ring Indicator				X			
8	CF	109	Received Line Signal Detector				X			
21	CG	110	Signal Quality Detector				X			
23	CH	111	Data Signal Rate Selector (DTE)					X		
23	CI	112	Data Signal Rate Selector (DCE)				X			
24	DA	113	Transmitter Signal Element Timing (DTE)							X
15	DB	114	Transmitter Signal Element Timing (DCE)						X	
17	DD	115	Receiver Signal Element Timing (DCE)						X	
14	SBA	118	Secondary Transmitted Data			X				
16	SBB	119	Secondary Received Data		X					
19	SCA	120	Secondary Request to Send					X		
13	SCB	121	Secondary Clear to Send				X			
12	SCF	122	Secondary Rec'd Line Signal Detector				X			

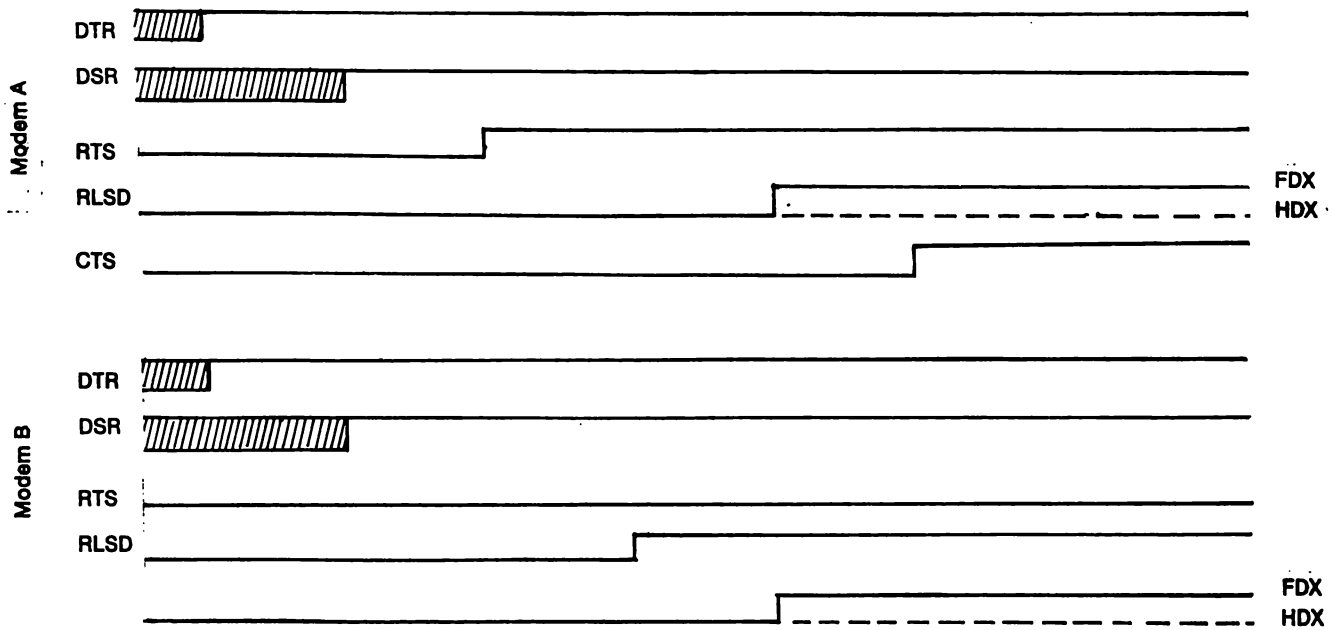
(D: p. 247)

(M: p. 328)

2.1 MODEMS/INTERFACES

INTERCONNECT EXCHANGE





DTR - Data Terminal Ready DSR - Data Set Ready RTS - Ready to send
RSLD - Received Line Signal Detector CTS - Clear to send

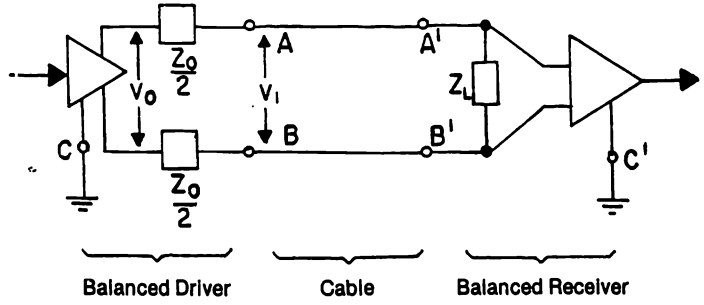
(D: p. 248) (M: p. 324)

2.1 MODEMS/INTERFACES (EIA RS 422/423/449)

- Replacement for RS - 232C
- Reduces crosstalk to permit long cables
- Allows higher data rate
- Incorporates new functions
- RS 422 - Electrical characteristics of balanced circuits
- RS 423 - Electrical characteristics of unbalanced circuits
- RS 449 - Functional and mechanical characteristics
- Equivalent to CCITT Recommendations V.10/V.11 and X.26/X.27

2.1 MODEMS/INTERFACES (EIA RS 422)

- 10 M bps maximum data rate
- 4000 foot maximum cable length



$|V_0| \leq 6\,V$

$Z_0 < 100\,\Omega$

V_1 maximum - greater of $2\,V$ or $\frac{V_0}{2}$

$V_A > V_B + 200\,mV$ Space/on

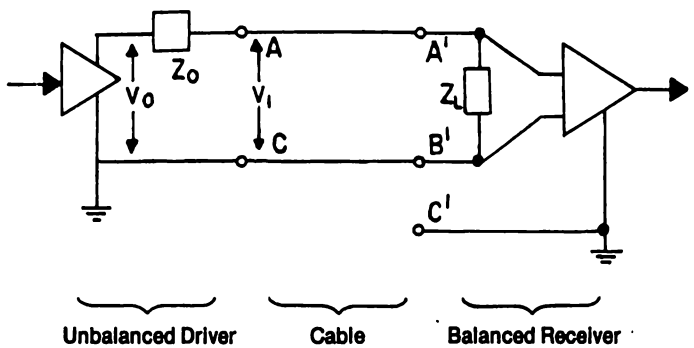
$V_B > V_A + 200\,mV$ Mark/off

$|V_{cm}| < 7\,V$

Z_L $100\,\Omega$

2.1 MODEMS/INTERFACES (EIA RS 423)

- 100 K bps maximum data rate
- 4000 foot maximum cable length



$4\,V \leq |V_O| \leq 6\,V$

$Z_O < 50\,\Omega$

$|V_I| \geq .9\,(V_O)$

$V_A > V_C + 200\,mV$ space/on

$V_C > V_A + 200\,mV$ mark/off

Z_L $450\,\Omega$

2.1 MODEMS/INTERFACES (EIA RS 449)

Circuit Mnemonic	Circuit Name	Circuit Direction	Circuit Type	
SG	Signal Ground		Common	
SC	Send Common	To DCE		
RC	Receive Common	From DCE		
IS	Terminal in Service	To DCE	Control	
IC	Incoming Call	From DCE		
TR	Terminal Ready	To DCE		
DM	Data Mode	From DCE		
SD	Send Data	To DCE	Data	Primary Channel
RD	Receive Data	From DCE		
TT	Terminal Timing	To DCE	Timing	
ST	Send Timing	From DCE		
RT	Receive Timing	From DCE		
RS	Request To Send	To DCE	Control	
CS	Clear To Send	From DCE		
RR	Receiver Ready	From DCE		
SO	Signal Quality	From DCE		
NS	New Signal	To DCE		
SF	Select Frequency	To DCE		
SR	Signaling Rate Selector	To DCE		
SI	Signaling Rate Indicator	From DCE		
SSD	Secondary Send Data	To DCE	Data	Secondary Channel
SRD	Secondary Receive Data	From DCE		
SRS	Secondary Request To Send	To DCE	Control	
SCS	Secondary Clear To Send	From DCE		
SRR	Secondary Receiver Ready	From DCE		
LL	Local Loopback	To DCE	Control	
RL	Remote Loopback	To DCE		
TM	Test Mode	From DCE		
SS	Select Standby	To DCE	Control	
SB	Standby Indicator	From DCE		

2.2 CODING AND CODES (OVERVIEW)

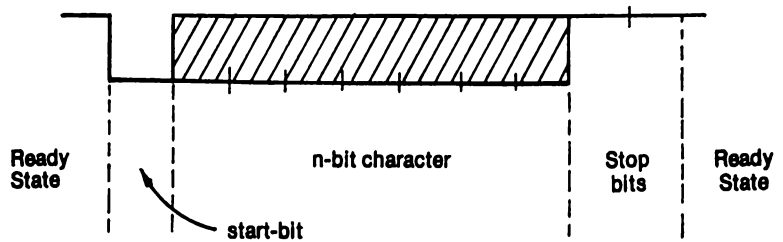
- Coding applications
  - Information
  - Error correction/detection
  - Encryption

2.2 CODING AND CODES (INFORMATION)

- Information consists of
  - Alphabet
  - Numerals
  - Punctuation
  - Special symbols
  - Format effectors
  - Device control characters
  - Transmission control characters
- n bits can uniquely encode 2^n symbols
- Asynchronous and synchronous transmission

ASYNCHRONOUS TRANSMISSION

- Also known as start-stop transmission



- Character by character transmission
- Start bit establishes bit timing
- Number of stop bits most commonly used
  1.0, 1.42, 1.5 or 2.0

(M: p. 54)

SYNCHRONOUS TRANSMISSION

- Bit timing usually derived from transistions in bit stream
- Data blocked into frames and bits are transmitted at clock rate
- Frame structure

Synchronization Sequence	Control Information	Variable Length Data	Error Checking

(T: pp. 165-174)

2.2 CODES AND CODING (CODES)

Code	CCITT#2	CCITT#5	ASCII	EBCDIC
Bits/character	5	7	7	8
Info. characters	49	87	94	98
Control characters	5	34	34	55

- Remarks
  - CCITT#2 - Alphabet extended by means of letters/figures shift
  - ASCII
    - ANSI standard
    - Assign seven unassigned sequences of CCITT#5
    - Parity bit is eight bit (even-asynch) (odd-synch)
  - EBCDIC
    - IBM standard
    - 103 user assignable characters

(M: pp. 58-67)

(D: pp. 241-242)

2.2 CODES AND CODING (CCITT ALPHABET #2)

Letters shift	Figures shift	Number of symbol	5-unit international code No. 2 (used by telex machines)
A	-	1	ZZAAA
B	?	2	ZAAZZ
C	:	3	AZZZA
D	Who are you?	4	ZAAZA
E	3	5	ZAAAA
F	*	6	ZAZZA
G	*	7	AZAZZ
H	*	8	AAZAZ
I	8	9	AZZAA
J	Bell	10	ZZAZA
K	(	11	ZZZZA
L	)	12	AZAAZ
M	.	13	AAZZZ
N	,	14	AAZZA
O	9	15	AAAZZ
P	0	16	AZZAZ
Q	1	17	ZZZAZ
R	4	18	AZAZA
S	'	19	ZAZAA
T	5	20	AAAAZ
U	7	21	ZZZAA
V	=	22	AZZZZ
W	2	23	ZZAAZ
X	/	24	ZAZZZ
Y	6	25	ZAZAZ
Z	+	26	ZAAAZ
<	Carriage return	27	AAAZA
≡	Line feed	28	AZAAA
↓	Letters	29	ZZZZZ
↑	Figures	30	ZZAZZ
■	Space	31	AAZAA
	(Not used)	32	AAAAA

(M: p. 59)

2.2 CODES AND CODING (CCITT ALPHABET #5)

Bit positions 5, 6, 7:

Bit positions 1, 2, 3, 4:		000	100	010	110	001	101	011	111
		0	1	2	3	4	5	6	7
0000	0	NUL	DLE	SP	0		P	'	p
1000	1	SOH	DC1	!	1	A	Q	a	q
0100	2	STX	DC2	"	2	B	R	b	r
1100	3	ETX	DC3	£	3	C	S	c	s
0010	4	EOT	DC4	$	4	D	T	d	t
1010	5	ENQ	NAK	%	5	E	U	e	u
0110	6	ACK	SYN	&	6	F	V	f	v
1110	7	BEL	ETB	'	7	G	W	g	w
0001	8	BS	CAN	(	8	H	X	h	x
1001	9	HT	EM	)	9	I	Y	i	y
0101	10	LF	SUB	*	:	J	Z	j	z
1101	11	VT	ESC	+	;	K		k	
0011	12	FF	FS	,	<	L		l	
1011	13	CR	GS	-	=	M		m	
0111	14	SO	RS	.	>	N	^	n	–
1111	15	SI	US	/	?	O	-	o	DEL

(M: p. 63)

2.2 CODES AND CODING (ASCII)

Bit positions 5, 6, 7:

Bit positions 1, 2, 3, 4:		000	100	010	110	001	101	011	111
		0	1	2	3	4	5	6	7
0000	0	NUL	DLE	SP	0	@	P	'	p
1000	1	SOH	DC1	!	1	A	Q	a	q
0100	2	STX	DC2	"	2	B	R	b	r
1100	3	ETX	DC3	#	3	C	S	c	s
0010	4	EOT	DC4	$	4	D	T	d	t
1010	5	ENQ	NAK	%	5	E	U	e	u
0110	6	ACK	SYN	&	6	F	V	f	v
1110	7	BEL	ETB	'	7	G	W	g	w
0001	8	BS	CAN	(	8	H	X	h	x
1001	9	HT	EM	)	9	I	Y	i	y
0101	10	LF	SUB	*	:	J	Z	j	z
1101	11	VT	ESC	+	;	K	[	k	{
0011	12	FF	FS	'	<	L	\	l	¦
1011	13	CR	GS	-	=	M	]	m	}
0111	14	SO	RS	.	>	N	^	n	~
1111	15	SI	US	/	?	O	-	o	DEL

(M: p. 66)

TRANSMISSION CONTROL CHARACTERS

ACK Acknowledge

A transmission control character transmitted by a receiver as an affirmative response to the sender.

DLE Data link escape

A transmission control character which will change the meaning of a limited number of contiguously following characters. It is used exclusively to provide supplementary data transmission control functions. Only graphic characters and transmission control characters can be used in DLE sequences.

ENQ Enquiry

A transmission control character used as a request for a response from a remote station - the response may include station identification and/or station status. When a "Who are you" function is required on the general switched transmission network, the first use of ENQ after the connection is established shall have the meaning "Who are you" (station identification). Subsequent use of ENQ may, or may not, include the function "Who are you", as determined by agreement.

EOT End of transmission

A transmission control character used to indicate the conclusion of the transmission of one or more texts.

ETB End of transmission block

A transmission control character used to indicate the end of a transmission block of data where data is divided into such blocks for transmission purposes.

ETX End of text

A transmission control character which terminates a text.

NAK Negative acknowledge

A transmission control character transmitted by a receiver as a negative response to the sender.

SOH Start of heading

A transmission control character used as the first character of a heading of an information message.

STX Start of text

A transmission control character which precedes a text and which is used to terminate a heading.

SYN Synchronous idle

A transmission control character used by a synchronous transmission system in the absence of any other character (idle condition) to provide a signal from which synchronism may be achieved or retained between data terminal equipment.

(M: p. 67)

BS Backspace

A format effector which moves the active position one character position backwards on the same line.

CR Carriage return

A format effector which moves the active position to the first character position on the same line.

FF Form feed

A format effector which advances the active position to the same character position on a pre-determined line of the next form or page.

HT Horizontal tabulation

A format effector which advances the active position to the next pre-determined character position on the same line.

LF Line feed

A format effector which advances the active position to the same character position of the next line.

VT Vertical tabulation

A format effector which advances the active position to the same character position on the next pre-determined line.

(M: p. 67)

2.2 CODES AND CODING (OTHER CHARACTERS)

DEVICE CONTROL CHARACTERS

DC_1 A device control character which is primarily intended for turning on or starting an ancillary device. If it is not required for this purpose, it may be used to restore a device to the basic mode of operation (see also DC_2 and DC_3), or for any other device control function not provided by other DCs.

DC_2 A device control character which is primarily intended for turning on or starting an ancillary device. If it is not required for this purpose, it may be used to set a device to a special mode of operation (in which case DC_1 is used to restore the device to the basic mode), or for any other device control function not provided by other DCs.

DC_3 A device control character which is primarily intended for turning off or stopping an ancillary device. This function may be a secondary level stop, for example wait, pause, stand-by or halt (in which case DC_1 is used to restore normal operation). If it is not required for this purpose, it may be used for any other ancillary device control function not provided by other DCs.

DC_4 A device control character which is primarily intended for turning off, stopping or interrupting an ancillary device. If it is not required for this purpose, it may be used for any other device control function not provided by other DCs.

INFORMATION SEPARATORS

IS_1 (US) A control character used to separate and qualify data logically; its specific meaning has to be defined for each application. If this character is used in hierarchical order as specified in the general definition of IS, it delimits a data item called a UNIT.

IS_2 (RS) A control character used to separate and qualify data logically; its specific meaning has to be defined for each application. If this character is used in hierarchical order as specified in the general definition of IS, it delimits a data item called a RECORD.

IS_3 (GS) A control character used to separate and qualify data logically; its specific meaning has to be defined for each application. If this character is used in hierarchical order as specified in the general definition of IS, it delimits a data item called a GROUP.

IS_4 (FS) A control character used to separate and qualify data logically; its specific meaning has to be defined for each application. If this character is used in hierarchical order as specified in the general definition of IS, it delimits a data item called a FILE.

(M: p. 64)

BEL Bell

A control character that is used when there is a need to call for attention; it may control alarm or attention devices.

CAN Cancel

A character, or the first character of a sequence, indicating that the data preceding it is in error. As a result, this data is to be ignored. The specific meaning of this character must be defined for each applicaton and/or between sender and recipient.

DEL Delete

A character used primarily to erase or obliterate an erroneous or unwanted character in punched tape. DEL characters may also serve to accomplish media-fill or time-fill. They may be inserted into or removed from a stream of data without affecting the information content of that stream but then the addition or removal of these characters may affect the information layout and/or the control of equipment.

EM End of medium

A control character that may be used to identify the physical end of a medium, or the end of the used portion of a medium, or the end of the wanted portion of data recorded on a medium. The position of this character does not necessarily correspond to the physical end of the medium.

ESC Escape

A control character which is used to provide additional control functions. It alters the meaning of a limited number of contiguously following bit combinations.

NUL Null

A control character used to accomplish media-fill or time-fill. NUL characters may be inserted into or removed from a stream of data without affecting the information content of that stream; but then the addition or removal of these characters may affect the information layout and/or the control of equipment.

SI Shift-in

A control character which is used in conjunction with SHIFT-OUT and ESCAPE to extend the graphic character set of the code. It may reinstate the standard meanings of the bit combinations which follow it.

SO Shift-out

A control character which is used in conjunction with SHIFT-IN and ESCAPE to extend the graphic character set of the code. It may alter the meaning of the bit combinations of columns 2 to 7 which follow it until a SHIFT-IN character is reached. However, the characters SPACE (2/0) and DELETE (7/15) are unaffected by SHIFT-OUT.

SP Space

A character which advances the active position one character position on the same line.

This character is also regarded as a non-printing graphic.

SUB Substitute character

A control character used in the place of a character that has been found to be invalid or in error. SUB is intended to be introduced by automatic means.

(M: p. 65)

2.2 CODES AND CODING (EBCDIC)

Bit positions 1,2,3,4

Bit positions 5,6,7,8	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111
0000	NUL				Blank	B	–						>	<		0
0001									a	j			A	J		1
0010									b	k	s		B	K	S	2
0011									c	l	t		C	L	T	3
0100	PF	RES	BYP	PN					d	m	u		D	M	U	4
0101	HT	NL	LF	RS					e	n	v		E	N	V	5
0110	LC	BS	EOB	UC					f	o	w		F	O	W	6
0111	DEL	IDL	PRE	EOT					g	p	x		G	P	X	7
1000									h	q	y		H	Q	Y	8
1001							/	"	i	r	z		I	R	Z	9
1010					?	!		;								
1011					.	S	,	#								
1100					←	*	%	@								
1101					(	)	⌣	'								
1110					+		–	=								
1111					*	¢	±	✓								

(D: p. 241)

ERROR CORRECTION/DETECTION

- Treatment of Errors
  - Ignore
  - Detect and ask for retransmission
  - Detect and correct
- Coding fundamentals
  - Redundancy
  - Distance
  - Detection capability
  - Correction capability
- Parity checking
- Hamming codes
- Cyclic redundancy check

(M: pp. 574-592)

(T: pp. 126-133)

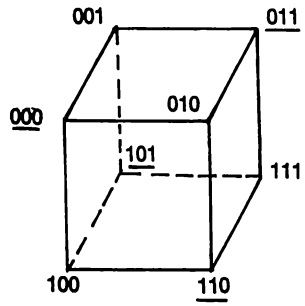
2.2 CODING AND CODES (CODING FUNDAMENTALS)

- Redundancy
  - n - bit code word containing m information bits and r redundancy bits
  - 2^m combinations - less than 2^n possible
  - valid and invalid code words
- Distance between two code words is the number of bits that must be changed to make the first code word change to the second
- Example: 1 0 1 1 0 1 0 and 1 0 0 1 0 1 1 have a distance of 2.

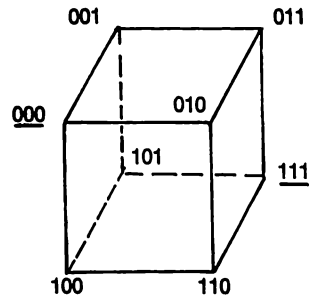
(T: p. 126)

2.2 CODING AND CODES (CODING FUNDAMENTALS)

- Error detection - to detect d-bit errors requires a (d +1) distance code
- Error correction - to correct d-bit errors requires a (2d +1) distance code
- Geometric interpretation examples



distance = 2



distance = 3

(T: p. 127)

2.2 CODING AND CODES (PARITY CHECKING)

- Parity - whether the total number of ones in a code word is an even or odd number.
- Distance = 2
- Parity bit normally appended at end of character
- Example: ASCII "W" 1 1 1 0 1 0 1 — $\begin{cases} 1 \text{ even} \\ 0 \text{ odd} \end{cases}$
- Block Parity

VRC (Vertical Redundancy check)

	1 0 1 0 0 1 0	0
	1 0 0 0 0 0 1	1
	1 0 0 1 1 0 0	0
	1 0 1 0 0 0 0	1
HRC	1 1 1 0 0 0 0	0

(Horizontal Redundancy Check)

(T: p. 127)

2.2 CODING AND CODES (HAMMING CODES)

- Uses theoretical minimum number of check bits to make single error correcting code
- Bits that are powers of 2 are check bits, others are information bits
- Example

ASCII "H"	1	0	0	1	0	0	0	
bit position	3	5	6	7	9	10	11	(even parity)
8					X	X	X	0
4		X	X	X				1
2	X		X	X		X	X	0
1	X	X		X	X		X	0

- Block transmission for burst error correction

(T: pp. 127-128)

CYCLIC REDUNDANCY CHECK

- Treats block of data as binary number
- Base 10 analogy

  210278 ÷ 10941 = 19 remainder 2399

  so (210278 - 2399) ÷10941 = 19 remainder 0
- "Divisor" is generator polynomial

  CRC-12 = $x^{12} + x^{11} + x^3 + x^2 + 1$

  CRC-16 = $x^{16} + x^{15} + x^2 + 1$

  CRC-CCITT = $x^{16} + x^{12} + x^5 + 1$
- Modulo 2 Arithmetic Rules
  - Addition and subtraction are exclusive or logic operation with no carries or borrow
  - A divisor is said "to go into" a dividend if the dividend has as many bits as the divisor

(T: pp. 128-130)

CYCLIC REDUNDANCY CHECK

- Encoding procedure

  1. Let r be the degree of the generator polynomial. Append r zero bits to the low-order end of the message.
  2. Divide message with appended zero bits by generator polynomial
  3. Subtract remainder (which is always r or fewer bits) from the dividend and transmit result

- Decoding procedure

  Divide received bit string by generator polynomial. If remainder is not zero, error(s) have occurred.

- Encoding and Decoding may be done with shift registers and exclusive or logic gates

(T: p. 130)

CYCLIC REDUNDANCY CHECK

- Example Message 1101011011
  Generator x^4+x+1

CYCLIC REDUNDANCY CHECK

- Power of CRC with r redundant bits
  - detects all single bit errors
  - detects all combinations of two bits in error
  - detects all combinations of odd number of bits in error
  - detects all burst errors of length $\leq r$ bits
  - detects r+1 bit burst errors with probability $1-(1/2)^{(r-1)}$
  - detects $> r+1$ bit burst errors with probability $1 - (1/2)^r$

(M: p. 580)

2.2 CODING AND CODES (ENCRYPTION)

- Military - KG, KY series equipment, etc.
- Civilian - Data Encryption Standard
  - Data Encryption Standard
    - 64 bit block of plain text encrypted in 64 bit block of cipher text
    - Algorithm uses a 56 bit key and 19 stages of permutations and substitutions
    - Same key used for encryption and decryption

(T: pp. 386-417)

3.1 COMMON CARRIERS (OVERVIEW)

- Common Carriers
- Specialized Common Carriers
- Value-Added Common Carriers
- International Carriers
- Regulatory Organizations
- Telephone System
  - Operations
  - Characteristics

3.1 COMMON CARRIERS

- Common carrier - A company which has been granted a franchise by a governmental regulatory body to provide communication services to the public at large

- Message Telecommunications Service
  - Local and long distance telephone service
  - A.T. & T. and 2000 others

- International Record Carriers
  - International cablegram, teletypewriter exchange, data, and facsimile service
  - Western Union International

- Specialized Common Carriers
  - Provide specialized transmission facilities
  - Microwave Communications Inc. (MCI)
  - Southern Pacific Communications Co.
  - Satellite Business Systems

(M: pp. 24-34)

(D: pp. 123-127)

3.1 COMMON CARRIERS

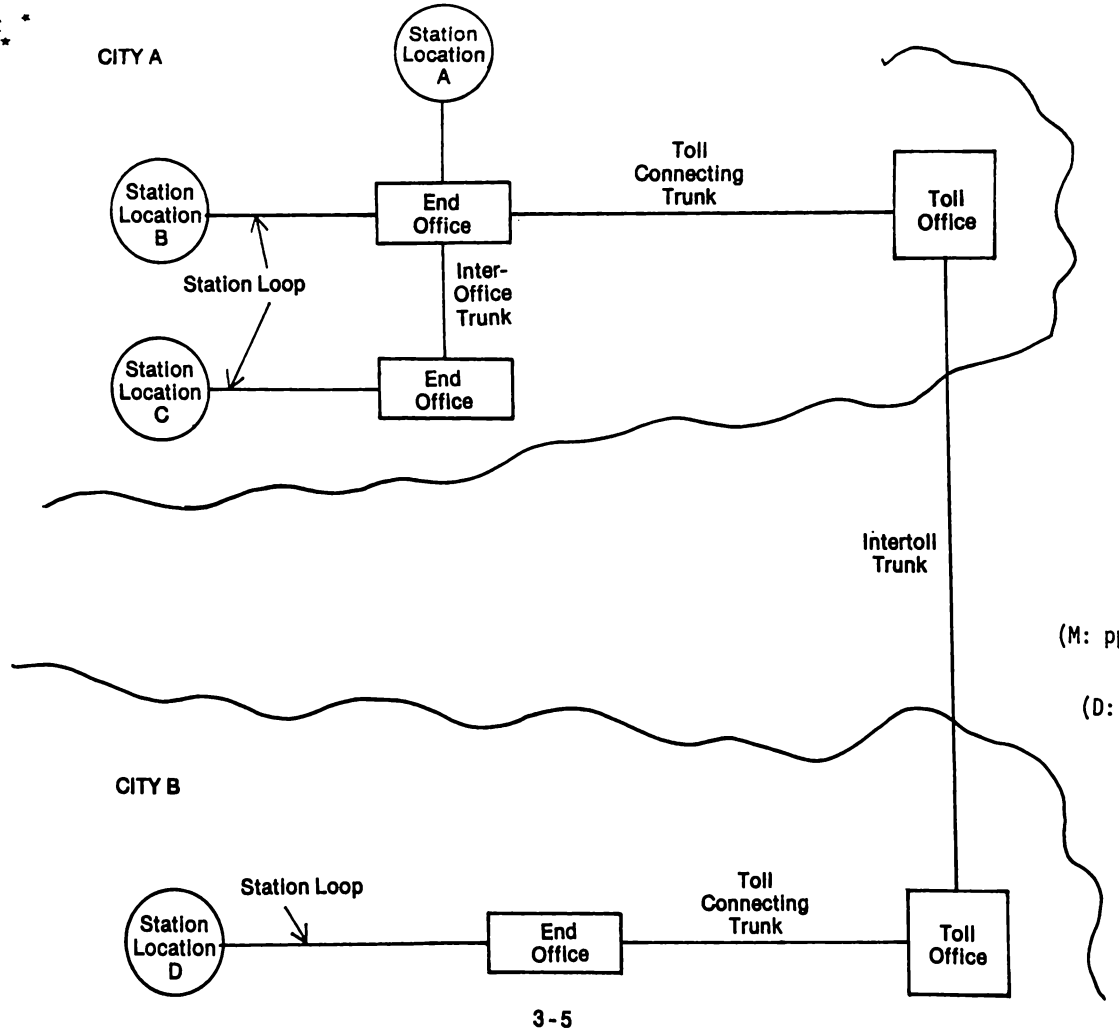
- Value Added Common Carriers
  - Leases links from other carriers and creates computer controlled network to provide new types of communications services
  - Telenet Communications Corp.
- International Carriers
  - ITT
  - RCA communications
  - Comsat
  - INTELSAT
- Regulatory Organizations
  - FCC
  - State Public Utilities Commission

(M: pp. 29-31, 34-37, 41-42)

3.1 COMMON CARRIERS (TELEPHONE SYSTEMS)

- Operations
  - Components
    - Station loops or local loops
    - End offices
    - Toll offices
    - Trunks
  - Switching
    - Hierarchial
    - High usage trunks
  - Services

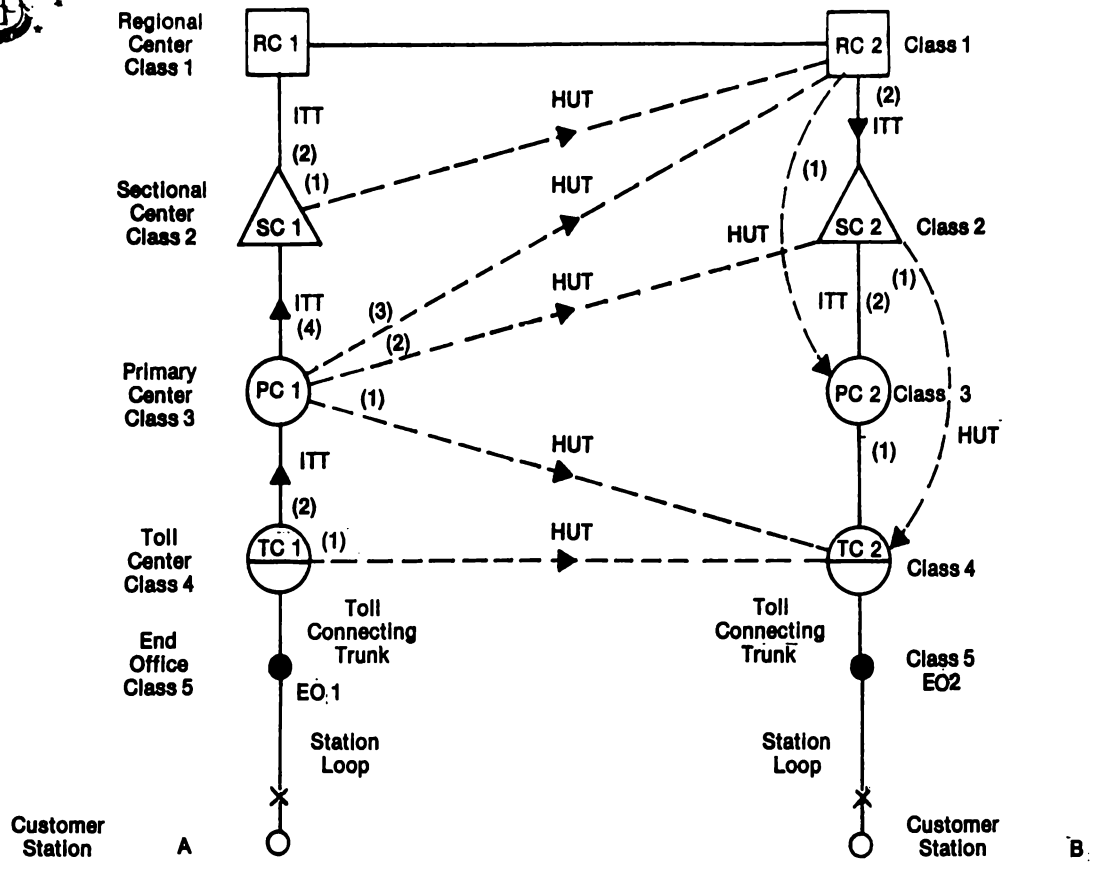
3.1 COMMON CARRIERS (COMPONENTS)



(M: pp. 362-363)

(D: p. 146)

3.1 COMMON CARRIERS (SWITCHING)



1. Numbers in ( ) indicate order of choice of route at each center for calls originating at EO 1.
2. Dashed lines indicate high-usage groups.
3. ITT - Intertoll Trunk
4. HUT - High Usage Intertoll Trunk

(D: pp. 144-149)

(M: pp. 362-369)

3.1 COMMON CARRIERS (SERVICES)

- WATS - Wide Area Telephone Service
  - Volume discount rate
  - Interstate vs. intrastate
  - Outward vs. inward
- Private Line Services
  - Multipoint drop
  - Conditioning
- Dataphone Digital Service
  - End to end, private line, baseband transmission service, either two-point or multipoint
  - Synchronous transmission
  - Up to 56 K bps data rate

(M: pp. 336-337, 342-347, 357-360)

(D: pp. 83-87, 97-107, 110-116)

TELEPHONE CHARACTERISTICS

- Conditioning
  - C conditioning - Uses equalizing filters to compensate for amplitude and phase variations
  - D conditioning - Use high quality circuits to control noise and harmonic distortion
- Error performance
  - Impulse noise prevalent
  - Burst errors
  - Frame error probability
    $P_E = 10^{-5} n^{0.8}$
  - Variance in performance

(M: pp. 526-530, 549-572)

TELEPHONE CHARACTERISTICS

Parameter	Linear conditioning spec			
		C1	C2	C4
Envelope delay distortion	800 2600 Hz 1750 μs	1000 to 2400 Hz 1000 μs	1000 to 2600 Hz 500 μs	1000 to 2600 Hz 300 μs
				800 to 2800 Hz 500 μs
			600 to 2600 Hz 1500 μs	
		800 to 2600 Hz 1750 μs		600 to 3000 Hz 1500 μs
			500 2800 Hz 3000 μs	
				500 to 3000 Hz 3000 μs
Frequency response relative to 1004 Hz	500 2500 Hz -2 to+8 dB	1000 to 2400 Hz -1 to+3 dB	500 to 2800 Hz -1 to+3 dB	500 to 3000 Hz -2 to+3 dB
	300 to 3000 Hz -3 to +12 dB	300 to 2700 Hz -2 to+6 dB	500 to 3000 Hz -2 to+6 dB	300 to 3200 Hz -2 to+6 dB
		300 to 3000 Hz -3 to +12 dB		

Parameter	Nonlinear conditioning spec
	D
Harmonic distortion	Fundamental to second harmonic: 35 dB minimum; to third harmonic 42 dB minimum
C-Notched Noise with 1004 Hz tone	Noise at least 28 dB below received 1004-Hz test tone

(M: pp. 526-530)

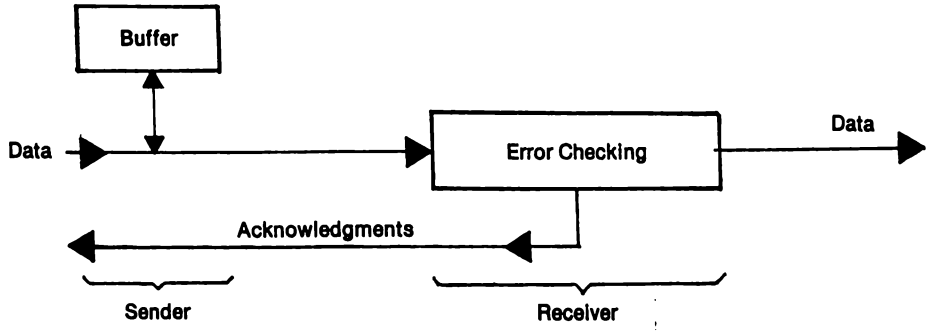
(D: pp. 176-179)

3.2 DATA LINK PROTOCOLS (OVER VIEW)

- Data link function - Transform raw transmission facility (physical layer) into virtually error free communication link
- Automatic Request for Retransmission (ARQ)
- Standard Protocols
  - Character oriented
  - Bit oriented

3.2 DATA LINK PROTOCOLS (ARQ)

- ARQ most often used
  - Less complex than forward error correction
  - Better throughput for typical error rates
- Two way exchange



(T: pp. 145-148)

(M: pp. 582, 589-592)

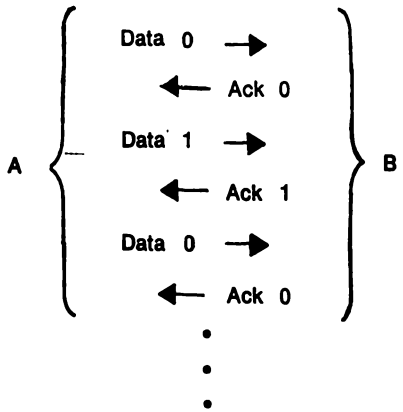
3.2 DATA LINK PROTOCOLS (ARQ)

- Stop and Wait Protocol Exchange
  - Sending IMP gets a packet, makes a frame out of the packet, stores it in a buffer for possible future use, transmits it and waits
  - Receiving IMP checks for errors, finds none and sends acknowledgment back to sending IMP
  - Sending IMP gets acknowledgment and begins exchange again
- Problems
  - Data frame lost or in error
  - Acknowledgment lost or in error
  - Receiving IMP dead

(T: pp. 145-148)

3.2 DATA LINK PROTOCOLS (SLIDING WINDOW)

- One bit sliding window stop and wait protocol
  - Alternately number data frames and acknowledgments 0 and 1
  - Exchange



  - Piggy backing - Acks contained within data frame if a data frame is ready
  - Synchronization difficulty with piggy backing if A and B simultaneously send

(T: pp. 148-153)

3.2 DATA LINK PROTOCOLS (PIPELINING)

- Stop and wait line utilization, $U = \frac{L}{L + BR}$

  L = frame length (bits)

  B = data rate (bps)

  R = round trip delay (sec)

- Example: Satellite with L = 1000 bits,

  B = 50 K bps R = 600 m S

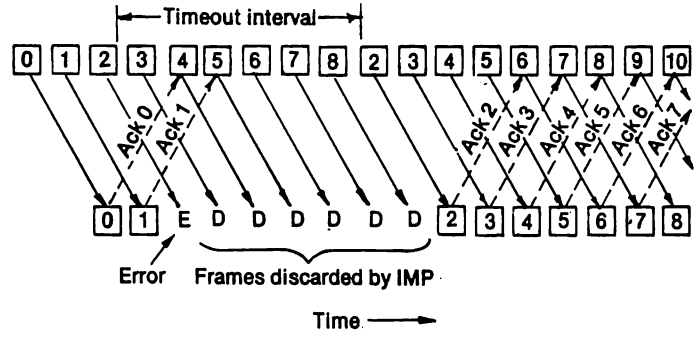
  $U = \frac{1000}{1000 + (50000)(.6)} = 3.2\%$

- Pipelining
  - Allows sender to send up to w frames without stopping
  - Go-back-n
  - Selective repeat

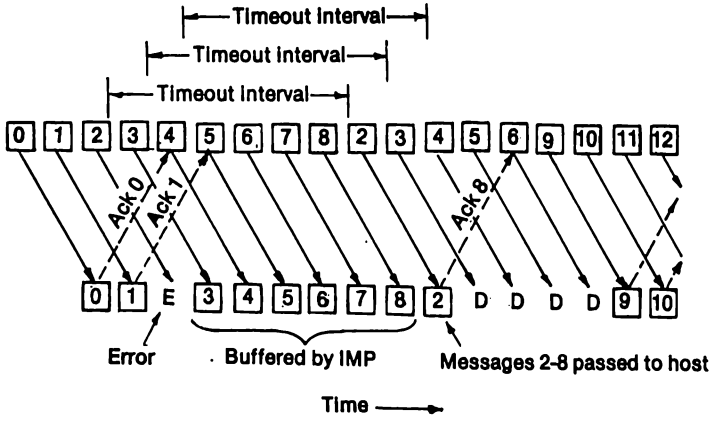
(T: pp. 153-154)

3.2 DATA LINK PROTOCOLS (PIPELINING)

- Go-back-n



- Selective Repeat



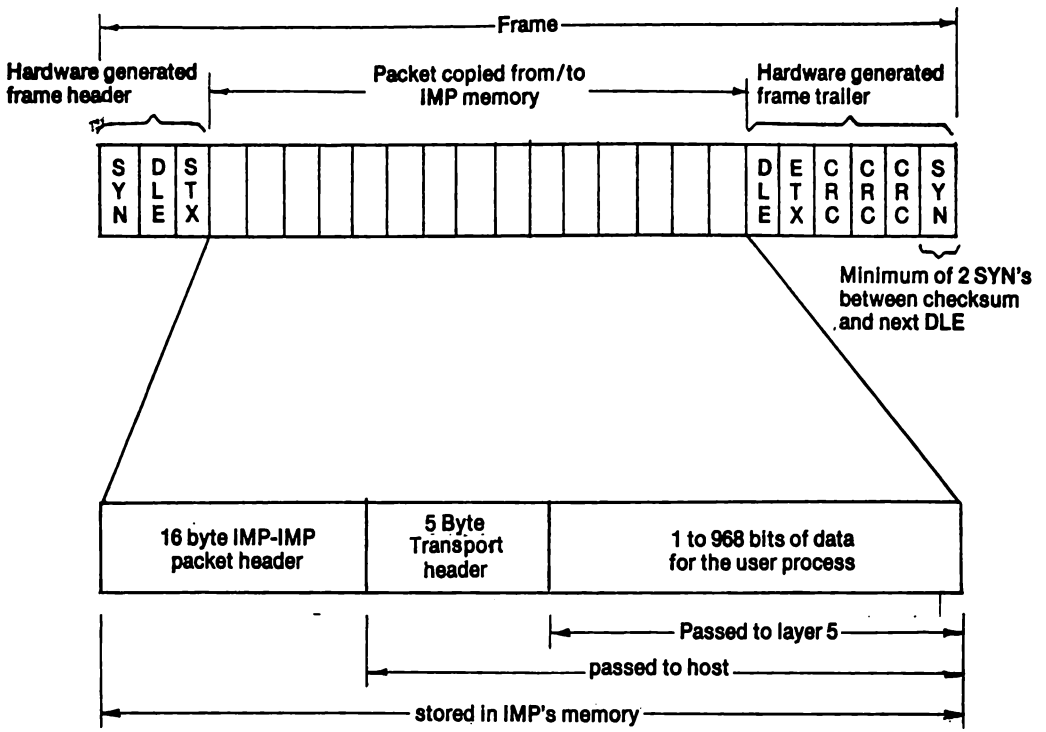
(T: pp. 153-164)

(M: pp. 581-583)

3.2 DATA LINK PROTOCOLS

CHARACTER ORIENTED

- Arpanet



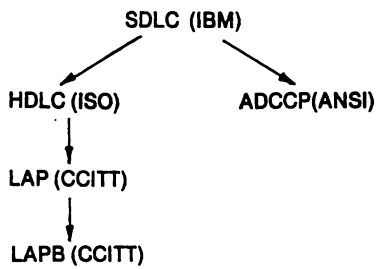
- Digital Data Communications Message Protocol (DDCMP)

Bits	8	14	11	8	8	8	16	8-131064	16
	SOH	Count		Ack	Seq	Addr	Header checksum	Data	Data checksum
			Sync / Select						

(T: pp. 165-167, 172-174)

3.2 DATA LINK PROTOCOLS (BIT ORIENTED)

- Relationship between protocols



SDLC - Synchronous Data Link Control

ADCCP - Advanced Data Communications Control Procedure

HDLC - High-level Data Link Control

LAP - Link Access Protocol

LAPB - B version of LAP

- Frame format

Bits	8	8	8	≥0	16	8
	01111110	Address	Control	Data	Checksum	01111110
	delimitor					delimitor

(T: pp. 167-169)

3.2 DATA LINK PROTOCOLS (BIT ORIENTED)

- Frame Types

Type	Control Field				
Bits	1	3		1	3
Information	0	Seq		P/F	Next
Supervisory	1	0	Type	P/F	Next
Unnumbered	1	1	Type	P/F	Modifier

(T: pp. 169-172)

3.3 BROADCAST NETWORK PROTOCOLS (OVERVIEW)

- Network Layer Function - controlling operation of subnet
- Satellite Packet Broadcasting
  - Conventional channel allocation methods
  - ALOHA
- Packet Radio

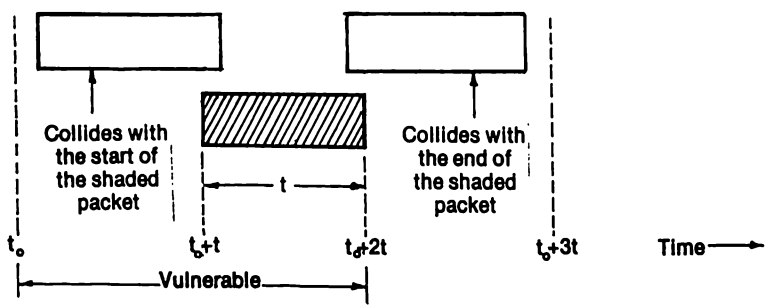
3.3 BROADCAST NETWORK PROTOCOLS (SATELLITE)

- Allocation of channel among independent users
- Satellite advantages
  - Simple error detection
  - No routing problem
  - Easy to add more users
  - Mobile users
- Conventional allocation methods
  - Polling
    - satellite
    - ground-based
  - Frequency division multiplexing
- ALOHA
  - Developed at University of Hawaii
  - Transmit when data is ready
  - Block data until successful transmission

(T: pp. 249-253)

3.3 BROADCAST NETWORK PROTOCOLS (ALOHA)

- Analysis of ALOHA
  - Large number of possible users generating new packets according to Poisson distribution
  - Fixed length packets
  - Packet time
  - Vulnerable period



- Pure ALOHA
  - S - average throughput per packet time
  - G - average number of attempts per packet time

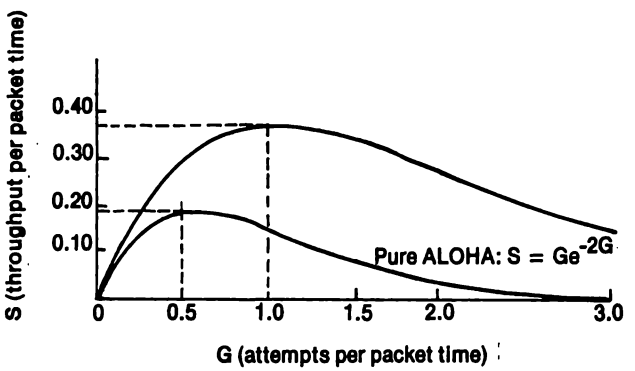
$$S = G e^{-2G}$$

(T: pp. 253-256)

3.3 BROADCAST NETWORK PROTOCOLS (ALOHA)

- Slotted ALOHA
  - Synchronization
  - Vulnerable period is half that of pure ALOHA

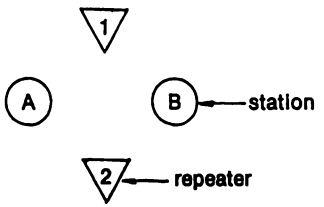
$$S = G e^{-G}$$



(T: pp. 256-257)

PACKET RADIO

- Repeaters
  - Store and forward operation
  - Routing problems



CASE I

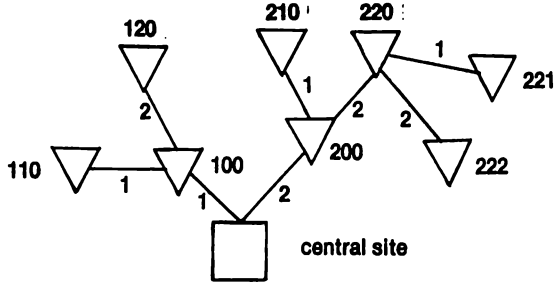
CASE II

- Solutions
  - Case I - single station served by more than one repeater
    - Do not allow situation to occur
    - Random waiting length

(T: p. 277)

PACKET RADIO

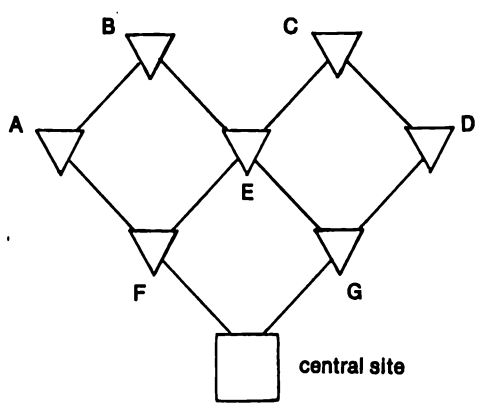
- Case II - infinite packet life
  - Hop counter in packet header
    - Decrement hop counter and transmit
    - Store last few packets to recognize reruns
  - Hierarchial
    - Probe packets transmitted to learn topology
    - Repeaters are then labeled



(T: pp. 277-281)

PACKET RADIO

- Relative distance
  - Requires knowledge at each repeater of how many hops to every other repeater
  - Each packet contains destination address and the sender's distance from the destination
  - If distance from next repeater to destination is less than sender's distance, send with new repeater distance



(T: pp. 281-282)

4.1 POINT TO POINT NETWORK PROTOCOLS

OVERVIEW

- Virtual circuits vs. datagrams
- Routing algorithms
  - Algorithm properties
  - Flooding
  - Static
  - Centralized
  - Isolated
  - Distributed
  - Hierarchial
- Congestion
- Dead locks or lockup
- Network protocol examples

4.1 POINT TO POINT NETWORK PROTOCOLS

- Virtual circuits vs. datagrams
  - Analogies
  - Comparisons

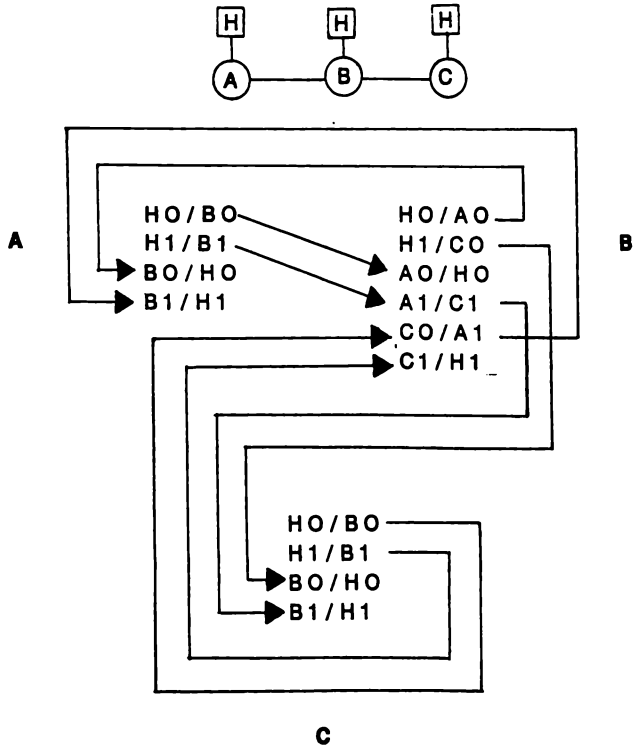
Issue	Virtual circuit	Datagram
Destination address	Only need during setup	Needed in every packet
Error handling	Transparent to host (done in the subnet)	Explicitly done by the host
End-to-end flow control	Provided by the subnet	Not provided by the subnet
Packet sequencing	Messages always passed to the host in the order sent	Messages passed to the host in the order they arrive
Initial setup	Required	Not possible

- Subnet internal structure
  - tables in memory of each IMP
  - operation for virtual circuits and datagrams

(T: pp. 187-192)

4.1 PT TO PT NETWORK PROTOCOLS

VIRTUAL CIRCUIT



Virtual circuits

Origin	Route	
A	A B	0
A	A B C	1
B	B A	0
B	B C	1
C	C B A	0
C	C B	1

- Subnet service

(T: pp. 192-196)

4.1 PT TO PT NETWORK PROTOCOLS (PROPERTIES)

- Desirable Properties
  - Correctness
  - Simplicity
  - Robustness
  - Stability
  - Fairness
  - Optimality
- Flooding
  - Every incoming packet is sent on every outgoing line except the incoming line
  - Hop counter for stability
  - Simple, robust, optimal
  - Selective flooding - flood in general direction of destination
  - Random walk - pick one outgoing line at random to send packet

(T: pp. 196-199)

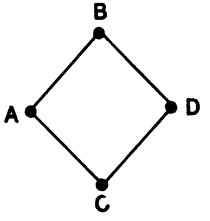
ROUTING ALGORITHMS

- Static or directory routing
  - Table with best, second best, third best, etc. choices for routing packet to each destination
  - Choose route by random, choosing best choice more often than second best, etc.
  - Optimality principle
  - Simple, correct, stable, fair
- Centralized routing
  - Similar to static routing except that routing table is updated periodically by routing control center (RCC)
  - IMP function fairly simple
  - RCC computations lengthy
  - RCC vulnerable
  - optimal, not robust

(T: pp. 199-202)

ROUTING ALGORITHMS

- Isolated routing
  - Adapt routing table by examining traffic
  - Hot potato algorithm
  - Backward learning
  - Delta routing
    - Hybrid form of centralized and isolated
    - "Cost" computations done at IMPs
    - Equivalent paths
- Distributed routing
  - IMPs exchange information about estimated time or hops to other IMPs



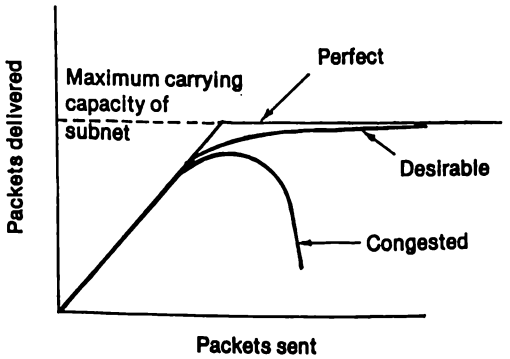
	B	C
A	30	20
B	0	40
C	50	0
D	70	30

Best route from A to D is A C D

(T: pp. 202-207)

ROUTING ALGORITHMS

- Hierarchial Routing
  - Used for networks with large number of IMPs
  - Divide network into regions
  - Optimum number of levels for N IMPs is ln N
- Congestion



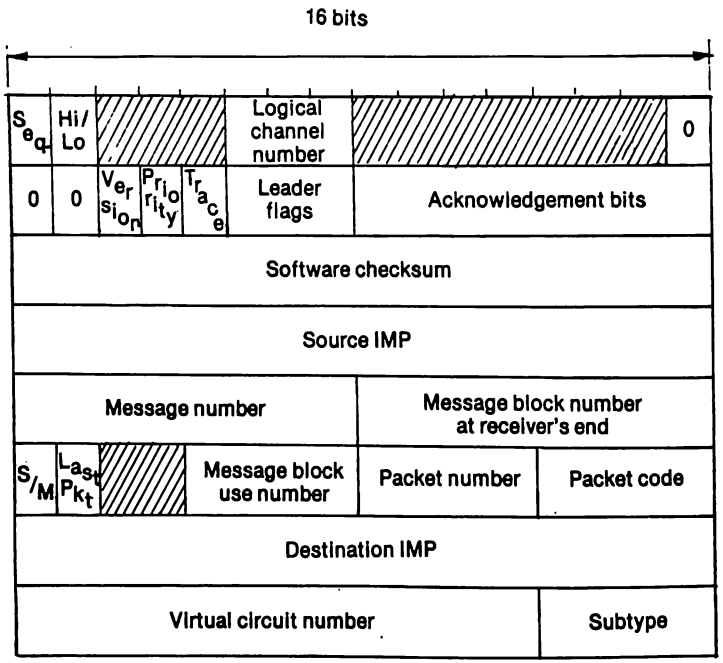
(T: pp. 211-212, 215)

4.1 PT TO PT NETWORK PROTOCOLS (CONGESTION)

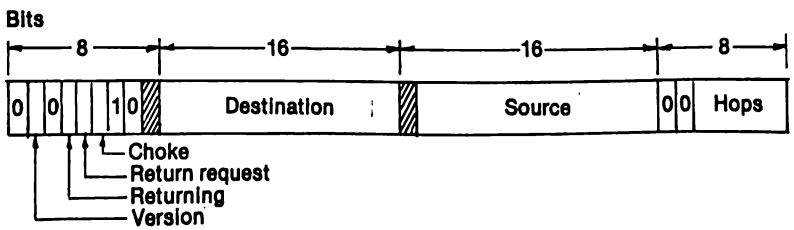
- Controlling congestion
  - Preallocating buffers
  - Packet Discarding
  - Isarithmic - constant number of packets in subnet
  - Flow control
  - Choke packets
- Dead locks or lockup
  - Total congestion

(T: pp. 215-225)

4.1 PT TO PT NETWORK PROTOCOLS



ARPANET Network Protocol



DECNET Network Layer Header

(T: pp. 226-231, 235-237)

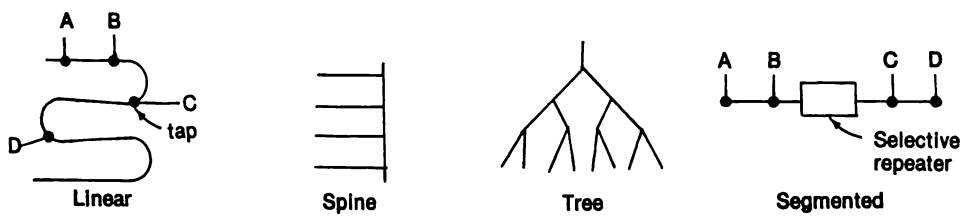
4.2 LOCAL NETWORK PROTOCOLS (OVERVIEW)

- Local network characteristics
  - Diameter less than a few kilometers
  - Total data rate exceeding 1 Mbps
  - Ownership by single organization
- Carrier sense networks
  - Persistent carrier sense multiple access
  - Non-persistent carrier sense multiple access
  - Ethernet
  - Collision free protocols
- Ring networks
- Shared memory networks

(T: pp. 286-288)

4.2 LOCAL NETWORK PROTOCOLS (CARRIER SENSE)

- Carrier Sense Multiple Access (CSMA)
  - Media usually coaxial cable, twisted pairs, or fiber optics
  - Topologies

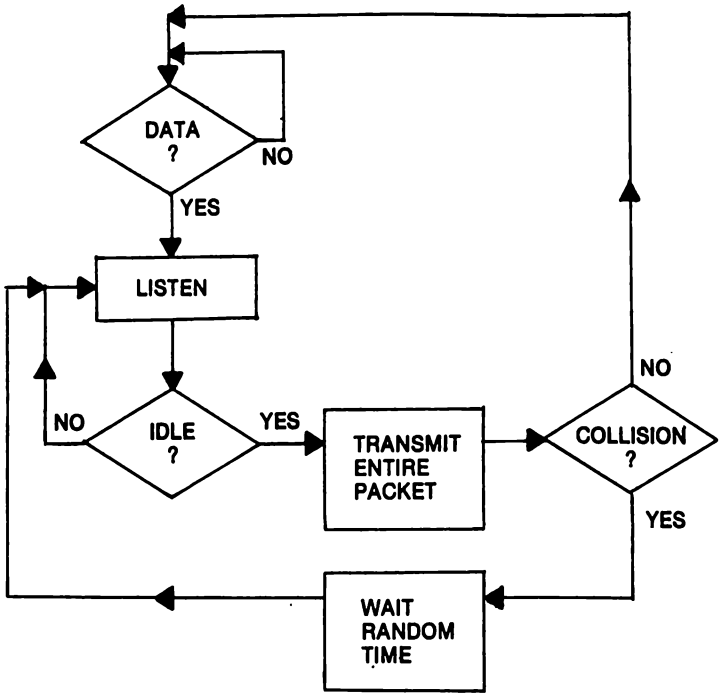


- Carrier sense operation - listen before transmitting

(T: pp. 288-289)

4.2 LOCAL NETWORK PROTOCOLS (CARRIER SENSE)

- I - persistent CSMA station flow chart

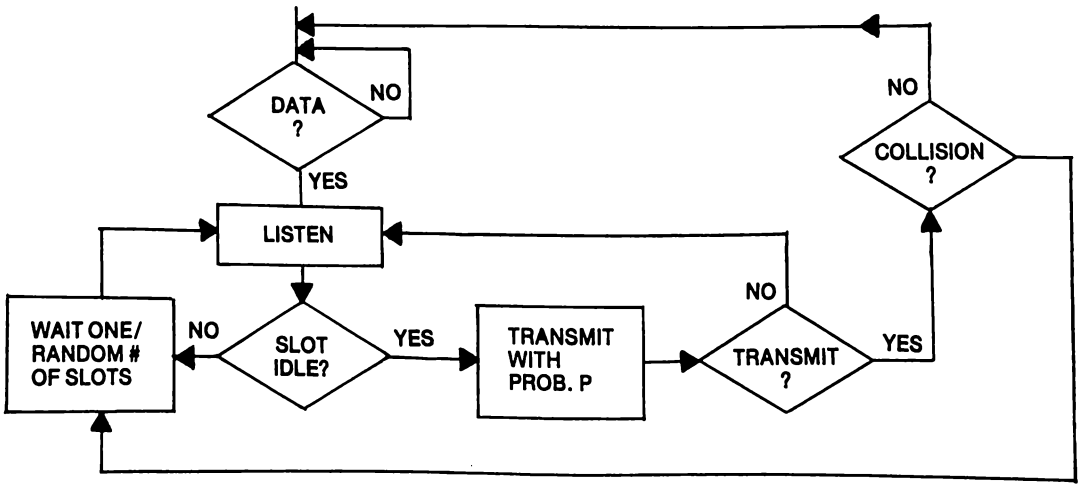


- Collisions
  - Due to media delay
  - Due to persistence

(T: pp. 289-291)

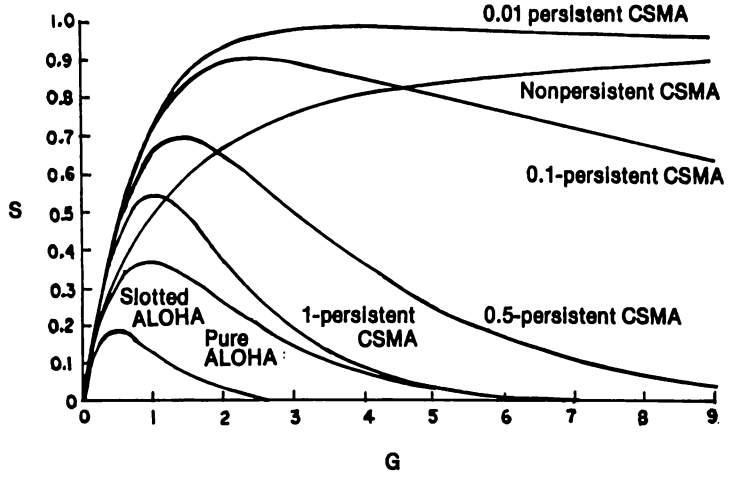
4.2 LOCAL NETWORK PROTOCOLS (CARRIER SENSE)

- Non - persistent CSMA
  - Similar to I-persistent CSMA except if channel is not idle, wait a random amount of time before listening
  - Better channel utilization and longer delays than I-persistent CSMA
- P - persistant CSMA
  - Applies to slotted channels
  - station flow chart



(T: pp. 289-291)

4.2 LOCAL NETWORK PROTOCOLS

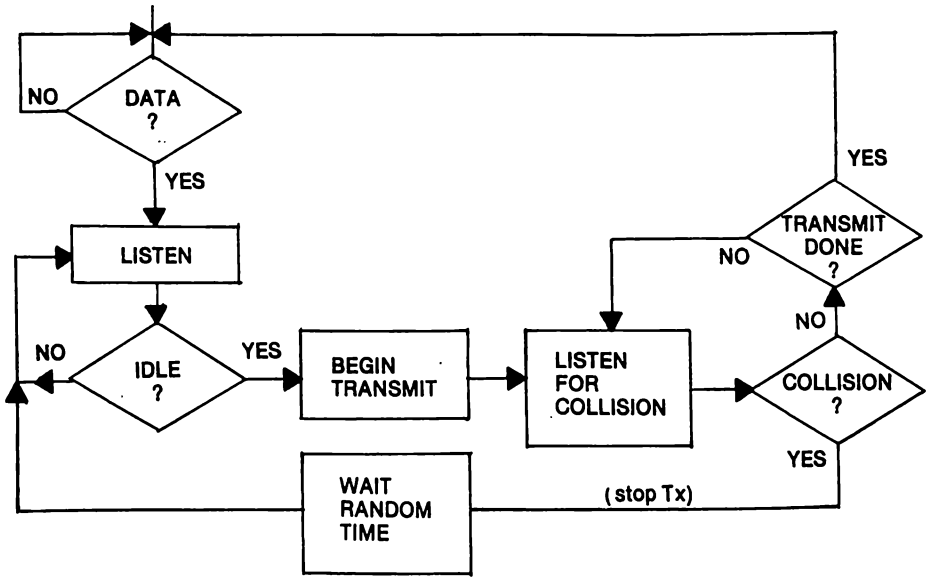


- Ethernet
  - Listen while transmitting
  - Terminate transmission immediately if a collision is detected

(T: p. 292)

4.2 LOCAL NETWORK PROTOCOLS (ETHERNET)

- Station flow chart

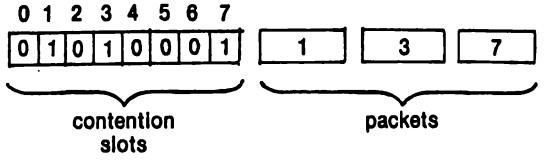


- Ethernet states
  - Idle
  - Transmission
  - Contention
- Channel efficiency $\bar{y} = \dfrac{P}{P + 5.4\tau}$ under heavy load

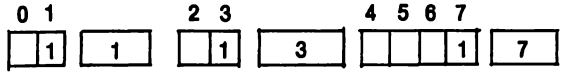
(T: pp. 292-295)

4.2 LOCAL NETWORK PROTOCOLS(COLLISION FREE)

- Collision-free protocols
  - Bit map



  - Broadcast recognition with alternating priorities (BRAP)



- Ring networks
- Shared memory networks

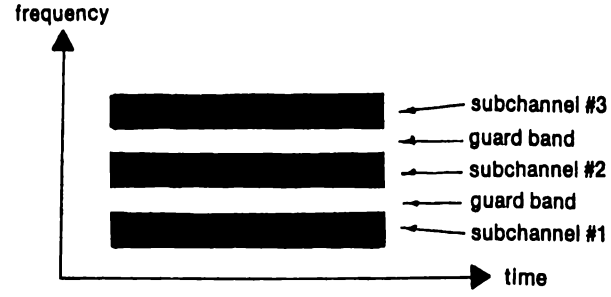
(T: pp. 296-320)

5.1 MULTIPLEXING/CONCENTRATION (OVERVIEW)

- Function - Sharing of a communications channel by several users to obtain cost-effective operation
- Multiplexing
  - Static allocation of frequency bands or time slots in a channel
  - Sum of input data rates equals output data rate
- Concentration
  - Dynamic allocation of frequency bands or time slots in a channel
  - Sum of maximum input data rates exceeds output rate
- Frequency Division Multiplexing (FDM)
- Synchronous Time Division Multiplexing (STDM)
- Message , packet switching concentration
- Line switching
- Statistical Time Division Multiplexing (STATDM)
- Inverse Multiplexing

(D: pp. 305-308)

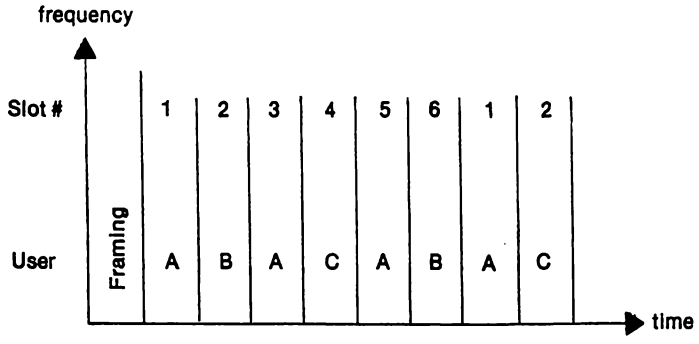
5.1 MULTIPLEXING/CONCENTRATION (FDM)



- Advantages
  - Cost effective
  - Code independent
  - Multi-drop capability easy to implement
- Disadvantages
  - Guard bands waste significant portions of available band width
  - Susceptible to intermodulation distortion

(D: pp. 308-311)

5.1 MULTIPLEXING/CONCENTRATION (STDM)

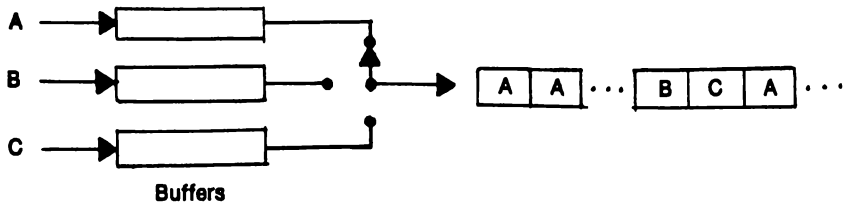


- Bit vs. character interleaving
- Buffered vs. unbuffered terminals
  - Unbuffered - Match scan rate to terminal data rate
  - Buffered - Adjust scan rate to minimize queuing delays
- Advantages - Uses bandwidth efficiently
- Disadvantages
  - Noise can cause synchronization problems
  - Synchronization required
  - Expensive for multi-drop
  - Non-active users waste bandwidth

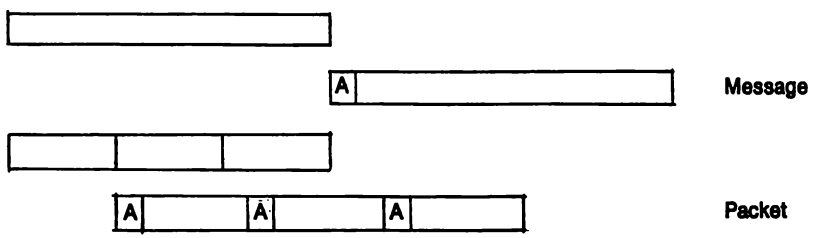
(D: pp. 311-316)

5.1 MULTIPLEXING/CONCENTRATION(SWITCHING)

- Message switching operation



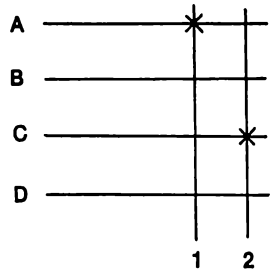
- Packet switching operation
  - Messages divided into fixed length packets
  - Packets sent in same manner as messages switching
- Both methods require each message or packet to have destination address
- Message switching vs packet switching



(D: pp. 327-330)

5.1 MULTIPLEXING/CONCENTRATION(SWITCHING)

- Line Switching
  - Also known as circuit switching
  - Bridges n inputs to m outputs on a demand basis
  - Connection remains for entire data transmission
  - Queuing delays while waiting for a line, but no delay when on a line



A ⟶ 1

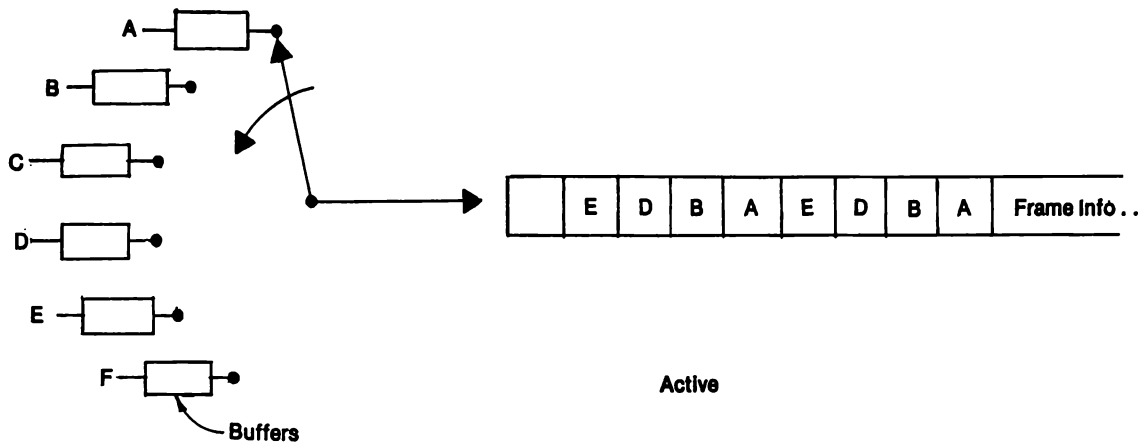
C ⟶ 2

B, D waiting

(D: pp. 330-334)

5.1 MULTIPLEXING/CONCENTRATION(STATDM)

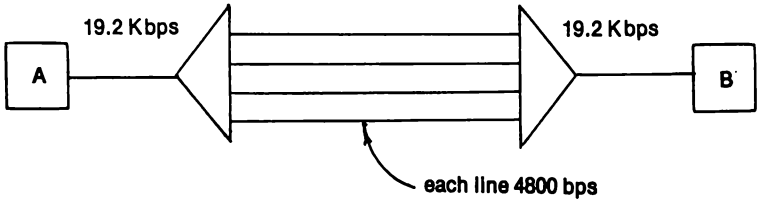
- Statistical Time Division Multiplexing
  - Hybrid form of STDM and message switching
  - Slots dynamically allocated to active users
  - Addressing methods
    - Addresses in time slots
    - Addresses at beginning of each frame
    - New addressing information whenever new subchannel established
    - Identify non-active users by means of a code word



(D: pp. 322-327)

5.1 MULTIPLEXING/CONCENTRATION

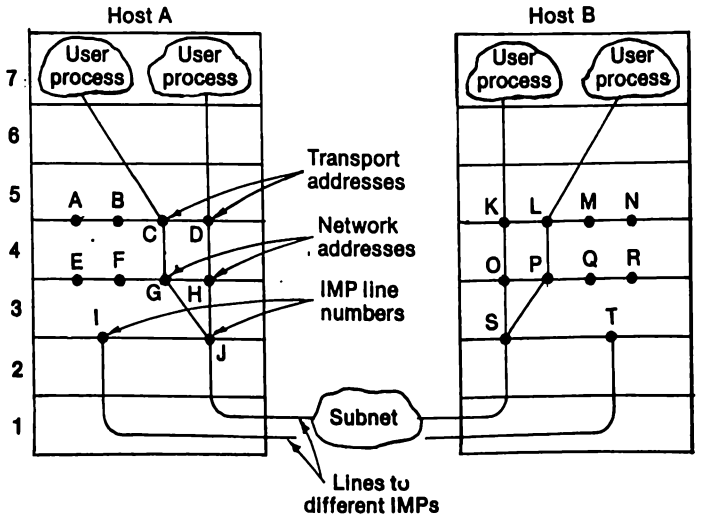
- Inverse multiplexing
  - Used when a high data rate channel is needed but several low data rate channels are more cost-effective
  - Example



(D: pp. 334-336)

5.2 TRANSPORT PROTOCOLS

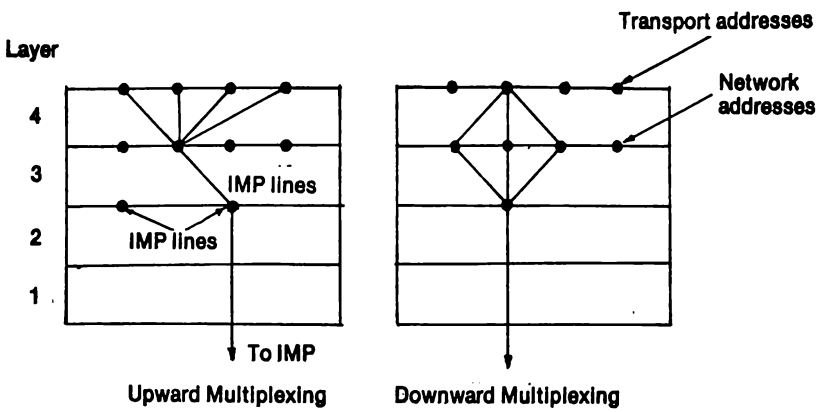
- Transport layer function - provide end-to-end data flow integrity in an efficient manner
- Transport service
  - Provided by layers 1 - 4
  - Layers 5 - 7 shield from details of transport service
  - Transport addresses
    - Network number, host number, port
    - Identifies user processes



(T: pp. 324-327)

5.2 TRANSPORT PROTOCOLS

- Hierarchial addresses
- Flat Address
- Multiplexing



- Decreasing error rate
- Crash recovery
  - Subnet crashes
  - Host crashes

(T: pp. 335-338, 343-345, 351-353)

5.2 TRANSPORT PROTOCOLS

- Delayed packets
  - Problem if sequence numbers in packets repeat in time less than longest lived packet
  - Solutions
    - Very large sequence numbers
    - Kill long lived packets in subnet
      - Restricted subnet design
      - Hop counter in packet
      - Time stamping each packet
- Interconnection of networks
  - Accomplish by gateways
  - Internetwork packet fragmentation

(T: pp. 345-351, 364-367)

5.3 DIGITAL VOICE COMMUNICATIONS (OVERVIEW)

- Advantages
- Nyquist Theorem
- Bell telephone digital system
- Other techniques

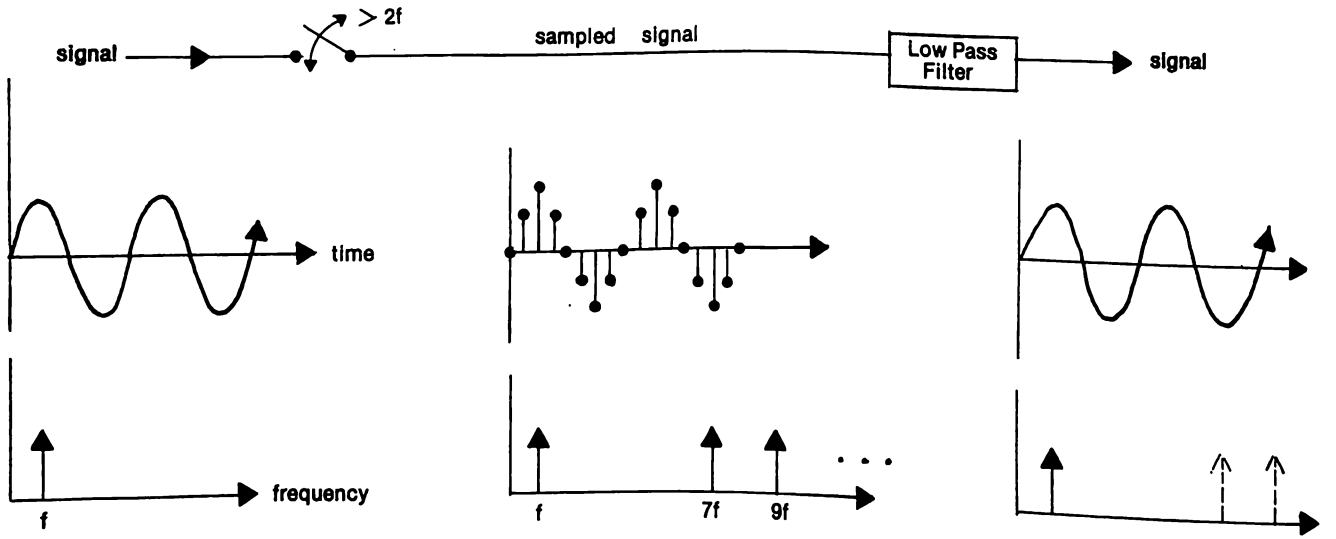
5.3 DIGITAL VOICE COMMUNICATIONS

- Advantages over analog voice communications
  - Better resistance to cumulative errors
  - Relatively easy to multiplex
- Coder/Decoders
  - Known as Codecs
  - Convert analog voice signal into digital signal
- Nyquist theorem
  - If the highest frequency in a signal is f, then sampling at a rate greater than 2f retains all the information in the signal.
  - Since high quality filters are very expensive, sampling is done at a rate 30 - 100% greater than 2f.

(T: pp. 104-105)

(M: pp. 263-270)

NYQUIST THEOREM



- Pulse Code Modulation (PCM)
  - Coder operation
    - Sample
    - Encode each sample into n bits

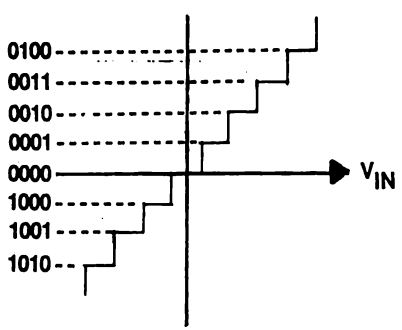
  Decoder operation
    - Decode n bits into analog voltage
    - Low-pass filter

(T: p. 105)

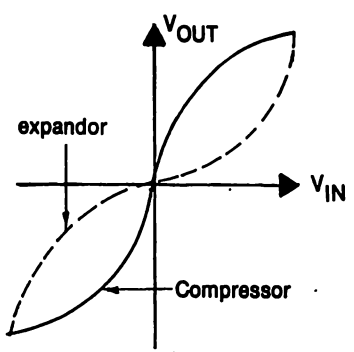
(M: pp. 268-270)

5.3 DIGITAL VOICE COMMUNICATIONS (PCM)

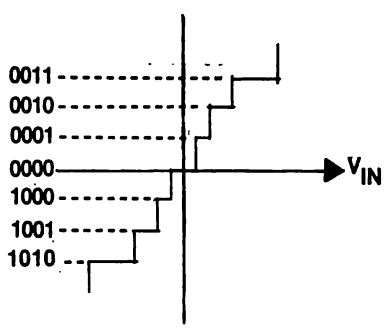
- Bandwidth required to send PCM signal is approximately n, the number of bits per sample, times the sampling frequency.
- Quantitization noise
  - Sampled signal rounded to nearest one of 2^n levels
  - Most noticeable with small amplitude signals
  - Companding
  - Non-linear quantitization



Linear quantitization



Companding

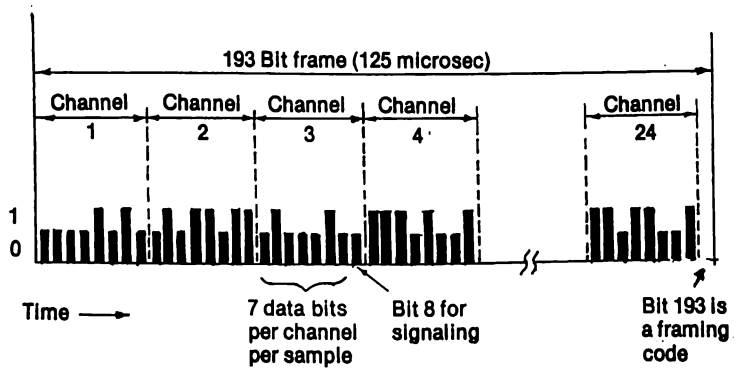


Non-linear quantitization

(M: p. 273)

5.3 DIGITAL VOICE COMMUNICATIONS (BELL SYSTEM)

- 24 voice channels on 1.544 M bps channel
- Sample at 8 K Hz rate
- Encode each sample into 8 bits
- Frame structure



(T: pp. 105-106)

(M: pp. 275-278)

OTHER TECHNIQUES

- Differential Pulse Code Modulation (DPCM)
  - Encode difference between last sample value and present sample value
  - Typically 5 bits per sample
- Delta Modulation
  - Similar to DPCM except difference may only be +1 or - 1
  - Rapidly varying signals cause problems
- Linear Predictive Coding
  - Algorithm takes last few sample values and predicts next sample value
  - Encode difference between actual and predicted value
  - Typically 1 - 3 bits per sample
- Vocoding
  - Speech analysis/synthesis
  - Typically 100 - 300 bps needed

(T: pp. 106-108)

NETWORK DESIGN (OVERVIEW)

- Topology Design
- The M/M/1 Network
- Delay Analysis
- Capacity Assignment
- Protocol Analysis

6.1 THE TOPOLOGY DESIGN PROBLEM

- PROBLEM FORMULATION

Given: Locations
Traffic
Cost

Performance: Reliability
Delay/Throughput

Variables: Topology
Line Capacities
Flow Assignment

Goal: Minimize Cost (or Delay)

(T: p. 33

6.1 THE TOPOLOGY DESIGN PROBLEM

- Example
  - Given: n locations
    - $\frac{n(n-1)}{2}$ potential lines

  - let n = 5 ⇒ 10 potential lines
    - $2^{n(n-1)/2}$ possible topologies
  - let n = 10 ⇒ $2^{45} = 3 \times 10^{13}$ possible topologies

    If 1 sec. to evaluate each ⇒ 1000 years to examine all

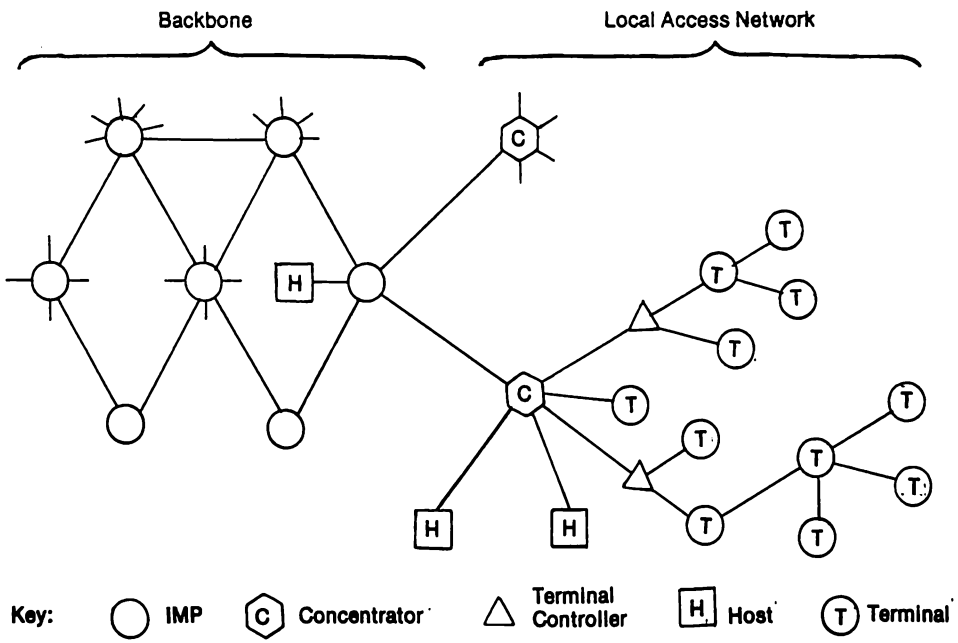
(T: p. 34)

6.13 THE TOPOLOGY DESIGN PROBLEM

- Strategies
  - Past Experience
  - Hierarchical Strategy
    - IMP's: Major Cities, Highly Redundant High Speed lines
    - Concentrators: Medium Size Cities, Medium Speed lines, Little Redundancy
    - Customer (Terminal): Leased/Dial-up Line To Nearest or IMP

(T: p. 34)

6.13 THE TOPOLOGY DESIGN PROBLEM



A TWO - LEVEL HIERARCHY

(T: p. 35)

6.14 THE TOPOLOGY DESIGN PROBLEM BECOMES SUBPROBLEMS

- Backbone Design
  - What should the backbone topology be
  - Assignment of line capacities
  - Flow assignment
- Local Access Design
  - Where to place concentrators
  - Which customers to assign to which concentrators
  - How to interconnect the terminals within a customer site
- Boundary
  - How to assign concentrators to IMP's

(T: pp. 35-36)

6.2 THE M/M/1 NETWORK

- REVIEW OF QUEUING THEORY
  - Time delay of messages is due to queuing at nodes
  - Actual delay depends on statistics of message arrival and servicing times
  - Overall network modeled as interactive network of queues
  - Queuing systems can be used to model processes in which customers (or messages) arrive, wait their turn for service, are serviced, and then depart.
  - Examples: Supermarket checkout stand, doctor's waiting rooms, etc.

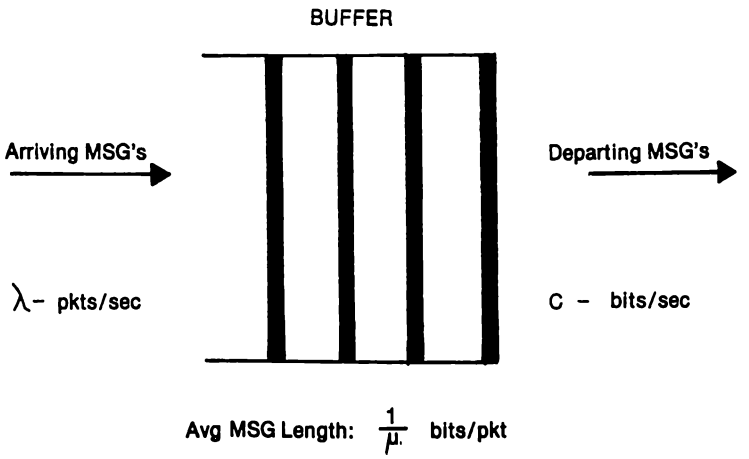
(T: p. 57)

6.2 THE M/M/1 NETWORK

- Components that characterize a queuing system
  - Interarrival-time probability density function
  - Service-time probability density function
  - Number of Servers
  - Queuing discipline
  - Amount of buffer space in the queue

(T: p. 57)

6.2 THE M/M/1 NETWORK



MODEL OF BUFFERING PROCESS AT CONCENTRATOR

(T: pp. 58-62)

6.2 THE M/M/1 NETWORK

- Tx takes place only if message is in queue
- Total time in system: (waiting+ service)
- Assumptions:
  - Infinite buffer size
  - Single server
  - First come, first serve

(T: pp. 58-59)

6.2 THE M/M/1 NETWORK

- Notation $\boxed{A/B/m}$

  where A - Interarrival time probability density

  B - Service time probability density

  m -number of servers

- Assumption $\boxed{M/M/1}$

  M - Markov (exponential probability density)

- Definition: Markov Process - process whose future depends only on its present value and not on its past behavior.

(T: p. 58)

6.2 THE M/M/1 NETWORK

- The probability of exactly "n" arrivals during an interval of length "t" is given by (Poisson)

$$P_n(t) = \frac{(\lambda t)^n}{n!} e^{-\lambda t}$$

where λ is the mean arrival rate

- Definition: 1. State of an M/M/1 queuing system - number of messages in the system (queue + server)

  2. M/M/1 in equilibrium - the probability of finding the system in a given state does not change with time

(T: pp. 58-59,

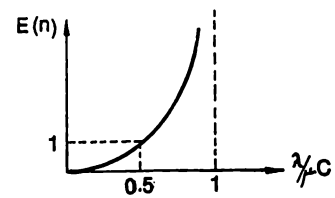
6.2 THE M/M/1 NETWORK

- The probability of the system being in state "k"

$$P_k = \left(1 - \frac{\lambda}{\mu C}\right)\left(\frac{\lambda}{\mu C}\right)^k$$

- The average queue size (or mean number of messages in system)

$$E(n) = \frac{\lambda}{\mu C - \lambda} = \frac{\lambda/\mu C}{1 - \lambda/\mu C}$$



- The average waiting time in system

$$E(T) = \frac{E(n)}{\lambda} = \frac{1}{\mu C - \lambda}$$

using Little's Formula: $E(n) = \lambda E(T)$

(T: p. 60-61)

6.2 THE M/M/1 NETWORK

Example: Consider a public birdbath at which birds arrive at an exponential rate (Poisson distribution). The mean arrival rate is 3 birds/min. The bathing time is exponential with a mean of 10 sec/bird. Find waiting time in the queue

Solution:

$$\lambda = 3 \frac{\text{birds}}{\text{min}} \times \frac{1}{60} \frac{\text{min}}{\text{sec}} = 0.05 \frac{\text{birds}}{\text{sec}}$$

$$\mu = 0.10 \frac{\text{birds}}{\text{sec}}$$

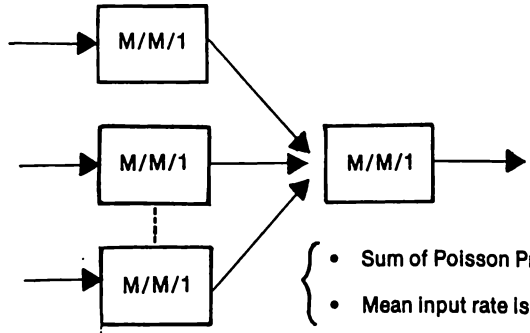
$$E(T) = \frac{1}{\mu - \lambda} = \frac{1}{0.05} = 20 \text{ sec} \quad \text{(waiting - service)}$$

Since mean service time $(\frac{1}{\mu})$ is 10 sec, the mean waiting time is

$$20 - 10 = 10 \text{ sec}$$

6.3 DELAY ANALYSIS

- Assumptions:
  - Each queue in network modeled as M/M/1 queue.
  - Each queue statistically indep of other queues.



- Sum of Poisson Processes is Poisson
- Mean input rate is sum of means

- Poisson Arrivals
- Exponential Msg lengths

(T: pp. 62-63)

6.3 DELAY ANALYSIS

- What is probability queue exceeds a specified number?
  - Infinite Buffer Size

$$\Pr(\text{Msg in queue} \quad N) = \rho^{N+1} = \left(\frac{\lambda}{\mu C}\right)^{N+1}$$

  - Finite Buffer Size

Pr (Buffer filled and msg's turned away (blocked))

= Pr (N msg's in buffer)

$$= \frac{(1-\rho)\rho^{N}}{1-\rho^{N+1}}$$

(T: pp. 60-62)

6.3 DELAY ANALYSIS

Example: Given $\rho = 0.6$

N	Pr (n>N)	Pr (msg blocked)
1	0.36	0.38
3	0.13	0.10
9	6.1×10^{-3}	4.1×10^{-3}
19	3.7×10^{-5}	2.4×10^{-5}

Infinite Buffer — Finite Buffer

- Recall average queue size (or occupancy) is

$$\frac{\rho}{1-\rho} = \frac{0.6}{1-0.6} = 1.5$$

- Note: A buffer that can hold 15 msg's appears effectively like an infinite buffer for this value of ρ.

6.3 DELAY ANALYSIS

- What is mean packet delay for network?
  - Apply Little's Formula: $E(T)\lambda = E(n)$
  - Let outgoing buffer associated with "l" link have

    $E(n_l)$ = avg. number of msg's waiting or in-service

    λ_l = avg. arrival rate

    $E(T_l)$ = avg. delay time
  - Visualize entire network as a "black box" or "big queue" with

    $E(n)$ = avg. number of msg's stored inside

    γ = avg. number of msg's that enter network

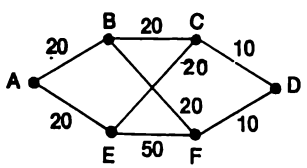
    $E(T)$ = avg. delay time for entire network

$$E(T) = \frac{1}{\gamma} \sum_{l=1}^{m} \lambda_l \, E(T_l)$$

(T: pp. 63-65)

6.3 DELAY ANALYSIS

Example: Given: the network of six - Imps and 8 - lines, with capacities in Kbps, as shown below, calculate mean packet delay for network.



Topology

Destination

Source	A	B	C	D	E	F
A		9 AB	4 ABC	1 ABFD	7 AE	4 AEF
B	9 BA		8 BC	3 BFD	2 BFE	4 BF
C	4 CBA	8 CB		3 CD	3 CE	2 CEF
D	1 DFBA	3 DFB	3 DC		3 DCE	4 DF
E	7 EA	2 EFB	3 EC	3 ECD		5 EF
F	4 FEA	4 FB	2 FEC	4 FD	5 FE	

"γ_{ij}" $\left(\frac{pkts}{sec}\right)$

"route"

Traffic and Routing Matrix

(T: p. 63)

6.3 DELAY ANALYSIS

Example (Cont.)

- Assume mean pkt size is 800 bits/pkt

i	Line	λ_i (pkts/sec)	C_i (Kbps)	μC_i (pkts/sec)	T_i (msec)
1	AB	14	20	25	91
2	BC	12	20	25	71
3	CD	6	10	12.5	154
4	AE	11	20	25	71
5	EF	13	50	62.5	20
6	FD	8	10	12.5	222
7	BF	10	20	25	67
8	EC	8	20	25	59

- Reverse traffic is same as forward and has same delay

(T: p. 64)

6.3 DELAY ANALYSIS

Example (Cont.)

$$E(T) = \frac{1}{\gamma} \sum_{l=1}^{m} \lambda_l E(T_l) = \bar{n} \sum_{l=1}^{m} \frac{\lambda_l E(T_l)}{\lambda}$$

where $\bar{n} = \frac{\lambda}{\gamma}$ ≡ mean number of hops/pkt

$\lambda = \sum_{l=1}^{m} \lambda_l$ ≡ total traffic on all lines

$E(T_l) = \frac{1}{\mu C_l - \lambda_l}$ ≡ l^{th} avg. delay time for channel "l"

$\gamma = \sum_{l=1}^{m} \sum_{l=1}^{m} \gamma_{lj}$ γ_{lj} ≡ avg. traffic between imp's i-j

(T: pp. 64-65)

6.3 DELAY ANALYSIS

Example (Cont.)

$$\gamma = \sum_{i=1}^{6} \sum_{j=1}^{6} \gamma_{ij} = 124 \quad , \quad \lambda = \sum_{i=1}^{8} \lambda_i = 82 \times 2 = 164$$

$$\bar{n} = \frac{\lambda}{\gamma} = \frac{164}{124} = 1.32$$

$$E(T) = 1.32\,(.0078 - 2(.0056) - .0057 - .0016 - .0108 - .0041 - .0029) \times 2$$

$$= 114 \text{ msec}$$

NOTE This is only an approximation to reality. For a given application exponentially distributed packet length may not be good. Also, we neglected components that contribute to delay such as time to compute checksum and propagation delay. We also neglected effect of errors, retransmissions, and control packets

(T: pp. 64-65)

6.3 DELAY ANALYSIS

Example (Cont.)

- Find probability that more than 5 messages are in queue at Imp "D". Assume infinite buffer space.

$$P_r(n > 5) = \rho^{5+1} = \left(\frac{\lambda_i}{\mu C_i}\right)^6 = \left(\frac{14}{25}\right)^6 = 0.03$$

$$E(n) = \frac{\rho}{1-\rho} = 1.27$$

- For Finite Buffer

$$\text{Pr (5 msg's in queue)} = \frac{(1-.56)\,(.56)^5}{1-(.56)^6}$$

$$= \frac{.44\,(.055)}{.969}$$

$$= .025$$

6.4 CAPACITY ASSIGNMENT

- Design Process
  - No exact solutions
  - Iteration process
    - choose starting topologies
    - assign the flows and capacities
    - modify network with perturbations
- Starting Topology
  - Constraint: Reliability
  - Use graph theory analysis (worst case)
  - Use Monte Carlo simulation (large networks)

(T: pp. 67-70)

6.4 CAPACITY ASSIGNMENT

- To calculate mean delay, we need λ_i on each link
- We must know routing algorithm to derive link traffic (γ_{ij})
- Some algorithms are dynamic vs static
- If the network is composed of many small, indep. customers, dynamic algorithm $\approx$ static model
- Flow Assignment
  - Shortest path routing
- Capacity Assignment Goal:
  - Calculate minimum cost to achieve prescribed delay
  - Assume linear cost function:

$$\text{total cost} = \sum_{i=1}^{m} (d_i C_i + x_i)$$

where d_i = cost/bps for line "i", C_i = capacity for line "i"

X_i = constant cost associated with each line

(T: p. 72)

6.4 CAPACITY ASSIGNMENT

- Goal: Minimize cost subject to time delay constraint:

$$\frac{1}{\gamma}\sum_{i=1}^{m}\frac{\lambda}{\mu C_i-\lambda_i} = E(T) = T$$

- Solution by Kleinrock (1964) gives optimal line capacities as:

$$C_i = \frac{\lambda_i}{\mu}\left[1+\frac{1}{\gamma T}\frac{\sum_{j=1}^{m}\sqrt{\lambda_j d_j}}{\sqrt{\lambda_i d_i}}\right]$$

- Then, total cost for network is

$$= \sum_{i=1}^{m}\left[d_i\frac{\lambda_i}{\mu}+X_i\right]+\frac{1}{\gamma T}\left[\sum_{i=1}^{m}\sqrt{\lambda_i d_i/\mu}\right]^2$$

- Note: This is gross simplification

(T: pp. 72-74)

6.4 CAPACITY ASSIGNMENT

Example. Use network in Section 6.3. Assume $d_i = 1$, $X_i = 0$ for all i. This means total cost of lines is just sum of their capacities. Assume $\frac{1}{\mu} = 800$ bits/pkt and goal is 100 msec packet delay. For the original network the total line capacities was 170 Kbps = 170 cost units and mean packet delay was 114 msec.

			Optimal		Uniform		Proportional		Original	
i	Line	λ_i	C_i	T_i	C_i	T_i	C_i	T_i	C_i	T_i
1	AB	14	23.5	65	18.6	108	25.4	56	20	91
2	BC	12	21.0	70	18.6	89	21.8	66	20	71
3	CD	6	12.8	100	18.6	58	10.9	131	10	154
4	AE	11	19.7	74	18.6	82	20.0	72	20	71
5	EF	13	22.2	68	18.6	98	23.6	61	50	20
6	FD	8	15.7	86	18.6	66	14.5	99	10	222
7	BF	10	18.4	77	18.6	75	18.1	79	20	67
8	EC	8	15.7	86	18.6	66	14.5	99	20	59

(T: p. 74)

6.4 CAPACITY ASSIGNMENT

- Example (Cont.)
  - Other assignment strategies
    - Uniform - each line given same capacity with sum equal to optimal (149 Kbps)
    - Proportional - 149 Kbps divided up so each line gets capacity in direct proportion to its traffic
  - Mean packet delay summaries

    Optimal — 100 msec

    Uniform — 111 msec

    Proportional — 102 msec

    Original — 114 msec
  - In this example, delay was not very sensitive to assignment since traffic was relatively uniform
  - Improved performance at lower cost

(T: pp. 74-75)

6.5 PROTOCOL ANALYSIS

- To evaluate protocol performance, need to determine channel efficiency of protocol
- Factors that influence protocol efficiency
  - frame length (fix or variable)
  - piggybacking used or not
  - pipelined or stop-and-wait
  - line half or full-duplex
  - statistical characteristics of transmission errors
- Need to determine how much bandwidth is used up to send the average frame

(T: p. 174)

6.5 PROTOCOL ANALYSIS

- Notation

A ≡ number of bits in an ACK frame

C ≡ channel capacity in bps

D ≡ number of data bits per frame

E ≡ probability of a bit being in error

F ≡ D+H (total frame length)

H ≡ number of bits in the frame lender

I ≡ interrupt and IMP service time+propagation delay

L ≡ probability that a frame or its ACK is lost or damaged

P_1 ≡ probability that a data frame is lost or damaged

P_2 ≡ probability that an ACK frame is lost or damaged

R ≡ mean number of retransmissions per data frame

T ≡ timeout interval

U ≡ channel utilization (efficiency)

W ≡ window size

(T: pp. 174-175)

6.5 PROTOCOL ANALYSIS

- Example: Stop-and-wait protocol, noiseless line

EXPRESSION	EVENT
F/C	Last bit sent
(F/C)+I	Last bit processed, IMP ready to send
(F/C)+(A/C)+I	Last bit of ACK sent
(F/C)+(A/C)+ 2 I	Sender processed ACK and ready to send next frame

$$\text{Frame BW} \equiv C \times (\text{time to transmit frame})$$

$$= C\,[(F/C)+(A/C)+2\,I]$$

$$= F+A+2\,IC$$

$$\text{Efficiency} \equiv \frac{\text{Data bits transferred}}{\text{Frame BW}}$$

$$= \frac{D}{H+D+A+2\,IC}$$

(T: p. 175)

6.5 PROTOCOL ANALYSIS

- Example: Stop-and-wait with noisy line

  R ≡ mean number of retransmissions per data frame

  - If a frame is damaged or lost, sender will time out T sec after last bit sent
  - Unsuccessful transmission uses F+ CT bits worth of transmission capacity
  - BW needed to send one good frame = R (F+ CT)+ (F+A+ 2 IC)

(T: p. 175)

6.5 PROTOCOL ANALYSIS

- Computing R, the mean number of retransmissions per frame

  - Frame Success ≡ Data and ACK frame correctly received

$$\Pr(\text{Fr. Success}) = \Pr(\text{Data Success}) \bullet \Pr(\text{ACK Success})$$
$$= (1 - P_2)(1 - P_1)$$

$$\Pr(\text{Fr. Failure}) \equiv L = 1 - \Pr(\text{Fr. Success}) = 1 - (1-P_1)(1 - P_2)$$

$$\Pr(\text{one Success in "K" attempts}) = pq^{k-1}$$
$$= \Pr(k-1 \text{ retransmissions}) = (1-L)(L)^{k-1}$$

$$\Rightarrow \quad R = \frac{L}{(1-L)}$$

(T: p. 175)

6.5 PROTOCOL ANALYSIS

- Example (Cont.)

  Using $R = L/(1-L)$

  $$U = \frac{D}{(L/(1-L))\ (F+CT)+(F+A+2CI)}$$

- If receiver service time has low variance, sender sets

  $T \approx A/C + 2I$

- Then

  $$U = \underbrace{\frac{D}{H+D}}_{\text{Header Loss}} \times \underbrace{(1-P_1)(1-P_2)}_{\text{Loss due to errors}} \times \underbrace{\frac{1}{1+CT/(H+D)}}_{\text{Stop-and-wait loss}}$$

- Assume bit errors are independent and equal

- Pr(Fr.Error) = 1 - Pr(Fr.Success)

- Pr (Fr. Success) = $\prod_{i=1}^{H+D} (1-E_i) = (1-E)^{H+D}$

(T: pp. 175-176)

6.5 PROTOCOL ANALYSIS

- Example (Cont.)

$$U = \frac{D}{H+D} \times (1-E)^{H+D} (1-E)^{H} \times \frac{1}{1+CT/(H+D)}$$

$$D_{opt} \approx \sqrt{\frac{(H+CT)}{E}}$$

- Other protocols
  - Go-Back-N

$$U = \frac{D}{H+D+R\,[W\,(H+D)+CT]}$$

  - Selective Repeat

$$U = \frac{D}{H+D+R(H+D)+N}$$

where N ≡ number of bits in NAK frame

(T: pp. 176-177)

6.5 PROTOCOL ANALYSIS

Example: Selective repeat protocol used on heavily loaded satellite channel with 50 Kbps bandwidth. Compute fraction of bandwidth that is wasted on headers and retransmissions when data frames consist of 40 header and 3960 data bits. ACK frames never occur. NAK frames are 40 bits. Data frame error rate is 1% and NAK frame errors are negligible

$$\text{BW (Wasted)} = \frac{H + R(H + D) + N/100}{H + D + R(H + D) + N/100}$$

$$R = \frac{L}{1 - L} \text{ and } L = 1 - (1 - P_1)(1 - P_2) = P_1$$

$$R = \frac{P1}{1 - P_1} = \frac{0.01}{0.99} \approx 0.01$$

$$\text{BW (Wasted)} = \frac{40 + 0.01\,(4000) + 40/100}{4000 + 0.01\,(4000) + 40/100} = 1.99\%$$

6.5 PROTOCOL ANALYSIS

- Noise on telephone lines
  - Empirical model

    $Pr\,(Fr.\ Error) = 10^{-4}\, m^{+0.8}$

    where $m \equiv$ number of 8-bit bytes/block
  - Burst Error model

    $Pr\,(Fr.\ Error) = (H + D) \times 2^{-r}$

    where $r \equiv$ number of bits in burst
  - Random errors are worst case

    Example: satellite links

(M: pp. 549-572)